Indian Head Division
Naval Surface Warfare Center
Indian Head, MD 20640-5035

IHTR 1799
15 June 1995

COMPATIBILITY TESTING OF HIGH DENSITY POLYETHYLENE (HDPE) FOR USE AS A SECONDARY CONTAINMENT LINER FOR A MIXED NITRATING ACID STORAGE TANK FARM

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REPORT DOCUMENTATION PAGE

Form Approved
QMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding the burden estimate or any other aspect of this collection of information, including suggestion for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports. 1215 Jefferson

1. AGENCY USE ONLY (*Leave Blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	15 June 1995	Final Report

4. TITLE AND SUBTITLE
COMPATIBILITY TESTING OF HIGH DENSITY POLYETHYLENE (HDPE) FOR USE AS A SECONDARY CONTAINMENT LINER FOR A MIXED NITRATING ACID STORAGE TANK FARM

5. FUNDING NUMBERS

6. AUTHOR(S)
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7. PERFORMING ORGANIZATIONS NAME(S) AND ADDRESS(ES)
Indian Head Division
Naval Surface Warfare Center
Indian Head, MD 20640-5035

8. PERFORMING ORGANIZATION REPORT NUMBER
IHTR 1799

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

The use of high density polyethylene (HDPE) as a secondary containment liner for a mixed nitrating acid storage tank facility was investigated. The chemical resistance and compatibility of HDPE with mixed nitrating acids (mixtures of nitric acid and sulfuric acid) was of primary concern. Weight, volume, specific gravity, and tensile properties of the polymer were used to evaluate the chemical resistance. Samples were immersed directly in various concentrations of mixed acid while cycling the temperature between hot and cold extremes.

14. SUBJECT TERMS

HDPE	Mixed acid	Spill containment
Nitric acid	Compatibility	
Sulfuric acid	High Density Polyethylene	

15. NUMBER OF PAGES 74

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN/640-01280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

FOREWORD

The work reported herein was performed at the Indian Head Division, Naval Surface Warfare Center, Indian Head, MD.

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INTRODUCTION

The outdoor mixed nitrating acid storage tank containment dike at the Indian Head Division, Naval Surface Warfare Center Biazzi Nitration Plant is constructed of a concrete slab and separately poured retaining walls. The joint between the retaining walls and floor has needed regular maintenance, frequently requiring the application of sealing compounds to eliminate leakage.

Long, thin fractures have also developed along the floor of the dike due to temperature fluctuations and earth settling throughout the dike's 11-year life. Additionally, contact with strong acids from fume condensation, sampling operations, and other exposure has deteriorated the concrete surface and integrity. The concrete has become spalled in some areas, breaking apart under little stress, and has required some resurfacing.

In order to slow the degradation of the dike, increase its integrity, and reduce maintenance, we searched for a cost-effective lining material which would meet the following criteria:

- Resistant to the various acid concentrations
- Flexible to prevent cracking due to earth settling and expansion
- Resistant to UV exposure from direct sunlight
- Capable of being applied over the surface of the dike and over the joints and cracks.

After a preliminary screening procedure of a variety of materials (Appendix A), the most cost-effective, resistant material appeared to be the high density polyethylene (HDPE) typically used in landfill and reservoir applications.

The HDPE lining material met all of the above criteria, but the chemical resistance appeared questionable. The manufacturer's specification sheet states that HDPE is suitable for secondary containment for sulfuric acid to 98% and in limited applications may be suitable for nitric acid to 100%, depending on specific conditions. A more extensive testing procedure was therefore developed to test the resistance of the HDPE to varying concentrations of nitric/sulfuric mixtures over time.

We felt that the liner must withstand a minimum of 48 hours of direct exposure to any given acid concentration it might experience. This would be sufficient to contain a spill until cleanup could be completed or the spill could be diluted to a concentration sustainable by the liner. This allows two full days after a spill for the acid to penetrate the liner and contact the concrete. The function of the concrete is then redefined from providing acid containment to that of providing a structural base for the containment liner.

EXPERIMENTAL

After preliminary screening, a sheet of 80 mil (0.080 inches nominal thickness) HDPE was obtained from SLT Corporation and cut into strips approximately 6 inches long and 2 inches wide. Seventy-eight samples were embossed, measured (length, width, and thickness) with a micrometer, and weighed (to 0.1 gram).

Four acid solutions were prepared from a solution of pure mixed nitrating acid. The pure mixed acid used consisted of 53% sulfuric acid and 47% nitric acid and is used in the production of propylene glycol dinitrate (PGDN), a nitrate ester and the primary component in the formulation of Otto Fuel II, the torpedo fuel for the Mks 46 and 48 torpedoes. These concentrations were used to simulate the varying concentrations of acidic media that might be encountered during a spill and over the life of the dike surface. The compositions were as follows:

Solution	Mixed Acid	Composition
1	5%	2.6% Sulfuric acid 2.4% Nitric acid 95% Water
2	30%	16% Sulfuric acid 14% Nitric acid 70% Water
3	65%	34% Sulfuric acid 31% Nitric acid 35% Water
4	100%	53% Sulfuric acid 47% Nitric acid

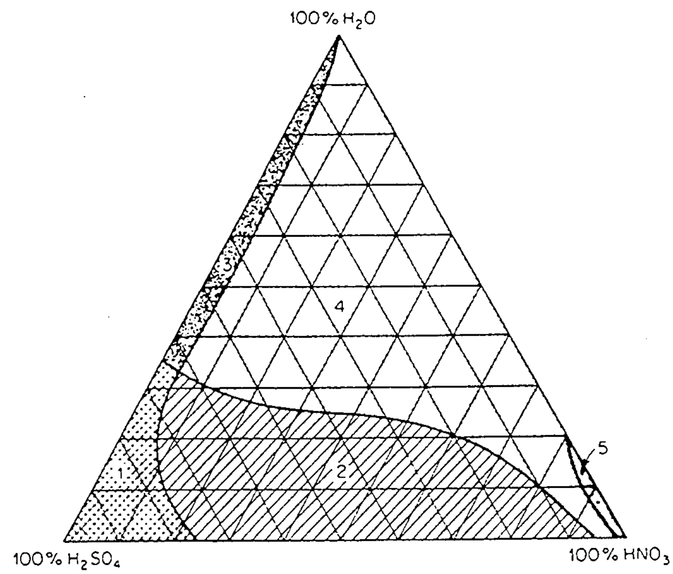
These concentrations were chosen based on the tertiary corrosion diagram for sulfuric/nitric/water mixtures in Figure 1. Each concentration change corresponds to a new corrosion zone or major deviation within a zone.

Eighteen samples were immersed in each solution. Six samples were not exposed to any acid and were used to determine baseline properties of the material. The temperature of the solutions were cycled between outdoor ambient temperature (averaging 30 to 40 °F) and 120 °F. High temperatures significantly increase corrosion attack, while temperature cycling allows the samples to expand and contract, thereby increasing potential exposure of the polymer structure to the acid solutions.

A temperature of 120 °F is a reasonable maximum temperature which might be expected on the surface of the dike during a spill cleanup. (The 100% mixed acid solution also emitted profuse fumes at temperatures greater than 120 °F.) Appendix B contains the raw data, laboratory notes, and temperature records of the acid solutions.

Six samples from each solution were withdrawn after 2, 5, and 15 temperature cycles (2, 8, and 23 days respectively). The final samples in the 100% mixed acid solution (solution 1) were withdrawn after 11 cycles (19 days) because they were badly deteriorated.

Each set of six samples withdrawn were washed first in fresh water, second in a solution of sodium carbonate, and lastly in fresh water. The samples were then dried in an oven at 120 °F until all visible moisture was gone. Each sample was remeasured and reweighed, then submitted for tensile properties testing.



CODE: (MATERIALS IN SHADED ZONES REPORTED CORROSION RATE LESS 20 MPY.)

	ZONE 1		
STEEL	GLASS	TANTALUM	GOLD
DURIMET 20	SILICON IRON	PLATINUM	
WORTHITE			
	ZONE 2		
CAST IRON	DURIMET 20	SILICON IRON	GOLD
STEEL	WORTHITE	TANTALUM	LEAD
18 CR-8 NI	GLASS	PLATINUM	
	ZONE 3		
DURIMET 20	GLASS	TANTALUM	GOLD
WORTHITE	SILICON IRON	PLATINUM	
	ZONE 4		
18 CR-8 NI	WORTHITE	SILICON IRON	PLATINUM
DURIMET 20	GLASS	TANTALUM	GOLD
	ZONE 5		
18 CR-8 NI	GLASS	TANTALUM	GOLD
DURIMET 20	SILICON IRON	PLATINUM	ALUMINUM
WORTHITE			

FIGURE 1. CORROSION RESISTANCE OF MATERIALS TO MIXTURES OF SULFURIC AND NITRIC ACID AT ROOM TEMPERATURE—LESS THAN 20 MILS PER YEAR
[Source: G.A. Nelson, Shell Development Co.]

RESULTS

Table I summarizes the physical properties and tensile properties of the samples before and after exposure to the acids.

TABLE I. HDPE/MIXED NITRATING ACID COMPATIBILITY STUDY RESULTS

Solution	Cycles	Days	Weight change (%)	Volume change (%)	Spec. grav. change (%)	Modulus of elasticity (psi)	Yield stress (psi)	Yield strain (%)	Maximum stress (%)	Maximum strain (%)
Baseline, no exposure			N/A	N/A	N/A	47,670	2,773	10.1	5,096	715
5%	2	2	0.23	2.51	−2.12	52,060	2,726	9.1	4,822	676
5%	5	8	0.00	−0.72	0.72	51,870	2,764	9.7	4,905	689
5%	15	23	0.00	−0.01	0.15	48,950	2,712	9.0	5,042	705
30%	2	2	0.58	−2.42	3.15	54,060	2,807	9.2	5,149	716
30%	5	8	0.11	0.85	−0.68	53,820	2,777	9.1	4,711	666
30%	15	23	0.33	0.57	−0.07	55,340	2,822	8.8	5,264	727
65%	2	2	0.21	0.60	−0.36	53,940	2,755	9.4	5,197	730
65%	5	8	0.32	1.35	−1.01	54,560	2,848	9.4	4,583	643
65%	15	23	0.55	0.97	−0.41	53,190	2,830	8.9	3,823	440
100%	2	2	1.48	1.51	0.16	47,508	2,714	9.8	5,269	777
100%	5	8	1.68	−2.43	4.22	50,490	1,962	7.8	1,968	8.3
100%	15	23	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Percent error[a]			1.2	4.1	4.3	6.1	2.1	5.1	11.0	9.2

[a]Percent error calculated for the physical properties from estimated experimental error. Percent error for tensile properties is the average standard deviation of the means. Percent error is the percentage error of the figures expressed in each column.

Physical Properties:

Appendix C contains experimental measurements and calculated values in spreadsheet form for the physical property data presented in Table I and discussed below.

Weight Gain: Figure 2 shows the percent weight gain after exposure in each acid solution and the experimental measurement error. All samples showed either no weight change or a slight increase in weight after exposure. None showed a weight decrease. This indicates that some acid solution may be absorbed into the HDPE and that if the HDPE is decomposed by the acid, more acid is absorbed than HDPE decomposed. Neither case is desirable.

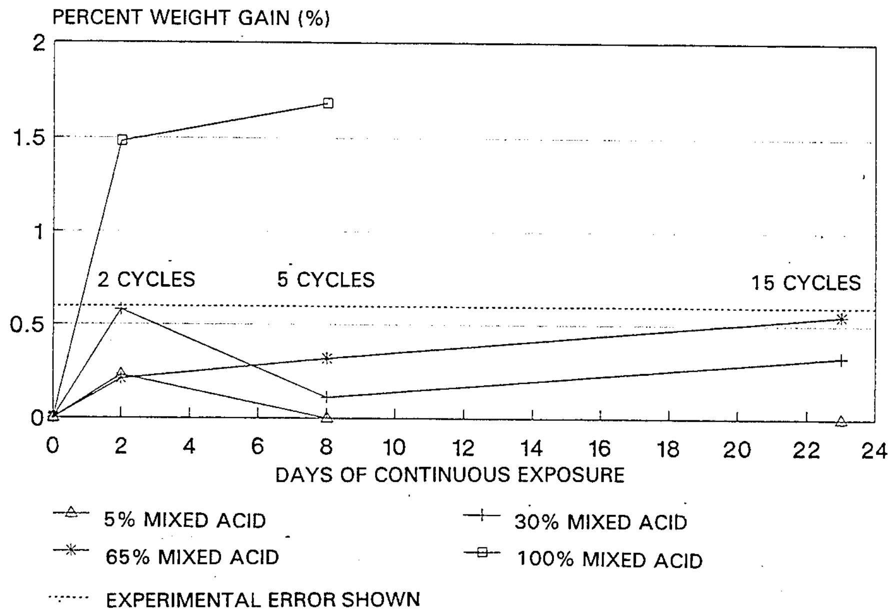


FIGURE 2. HDPE WEIGHT GAIN FROM ACID EXPOSURE

An alternative explanation may be that the acid is chemically reacting with the polyethylene, forming a new product, which stays associated with the HDPE structure rather than the acid phase.

The weight gains for all acid solutions except the pure acid solution, however, were within the experimental measurement error discussed later; thus, only the weight gain in the 100% acid solution is a conclusive weight gain.

Volume Change and Specific Gravity Change: The volume change calculation was based on sample volume determination by length, width, and thickness measurements rather than by the standard immersion procedure due to the low specific gravity of the samples (they float in most liquids).

The 4.1% and 4.3% errors shown in Table I represent the error from actual values, which are taken to be the mean of several measurements along each dimension of the sample. To ensure that measurements were taken from the same point before and after immersion, however, all measurements were taken only from one point, the corner of the embossment. Therefore, if a sample's corners are not precisely square, the error will be greatest when taking measurements at a corner. This is the probable cause for the large standard deviations in sample volume and specific gravity changes (See Appendix C). Note that some data show increases while some show decreases in both of these properties.

Tensile Properties:

Tensile property testing was conducted in accordance with ASTM Specification D638/D882 (Type IV Dumbell). The crosshead speed (pulling speed of the sample) was set at 2.000 inches per minute. This is the standard testing method used by most manufacturers of HDPE linings in their tensile property publications.

Appendix D contains the tensile property test data, graphs, and photographs of the HDPE samples before and after immersion. These results are summarized in Table I and discussed below.

Figure 3 is an example of a stress-strain curve for HDPE. The slope of the straight line drawn through the origin is the modulus of elasticity. The modulus of elasticity is a measure of the stiffness, or rigidity, of the material before it has been stretched. The higher the modulus of elasticity, or the steeper the slope of the line, the stiffer the material.

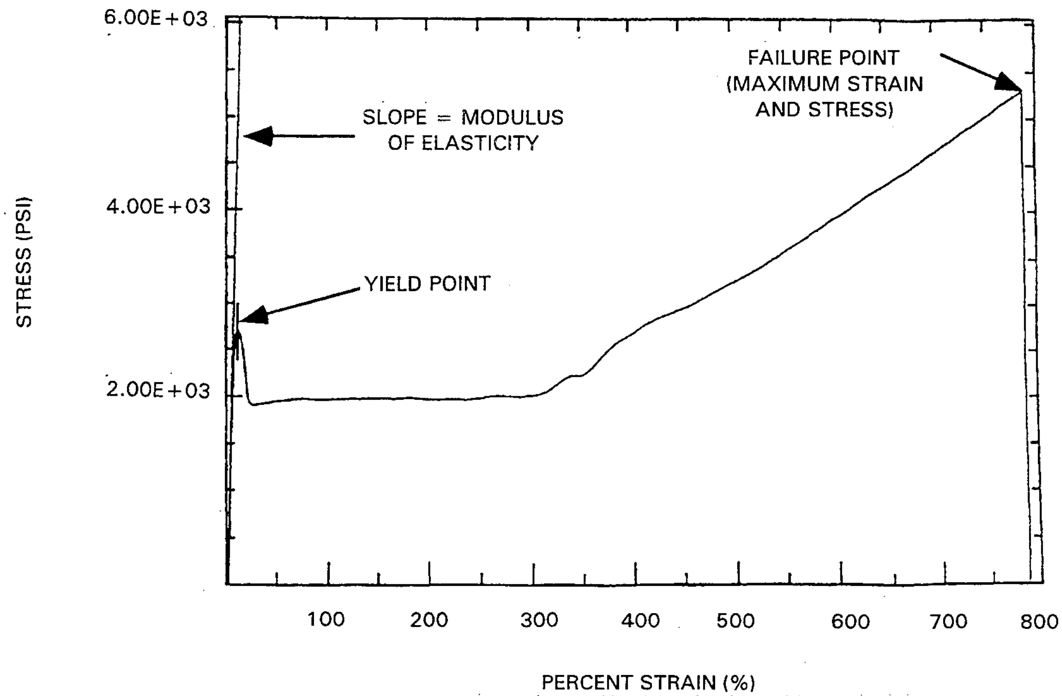


FIGURE 3. HDPE STRESS-STRAIN CURVE

The yield point is the point on the curve where the first maximum is reached. The yield stress (force per area) and yield strain (percent elongation) are the stress applied and strain induced at that point. At this point the polymer chains start to separate, and irreversible destruction of the polymer begins. Prior to the yield point the polymer will return to its original shape if the stress is removed. This is known as the "rubber band effect."

After the sample yields, it will then stretch for a time under constant stress. As the sample is stretched still further, the stress will begin to increase linearly with increases in strain. In this region the polymer chains are being stretched to their limit; they are thereby getting stiffer and more force is required to stretch the sample. The sample then reaches the failure point and tears.

Modulus of Elasticity: Figure 4 shows the change in the HDPE modulus of elasticity over the exposure times in each acid concentration. The data show that there is roughly no change in the modulus of elasticity over the exposure times; all data after exposure are within one standard deviation of the nonexposed sample. This indicates that there is no change in the stiffness of the material prior to stretching. The material will retain its rigidity even after it has been exposed to acid as long as no stress is placed on it.

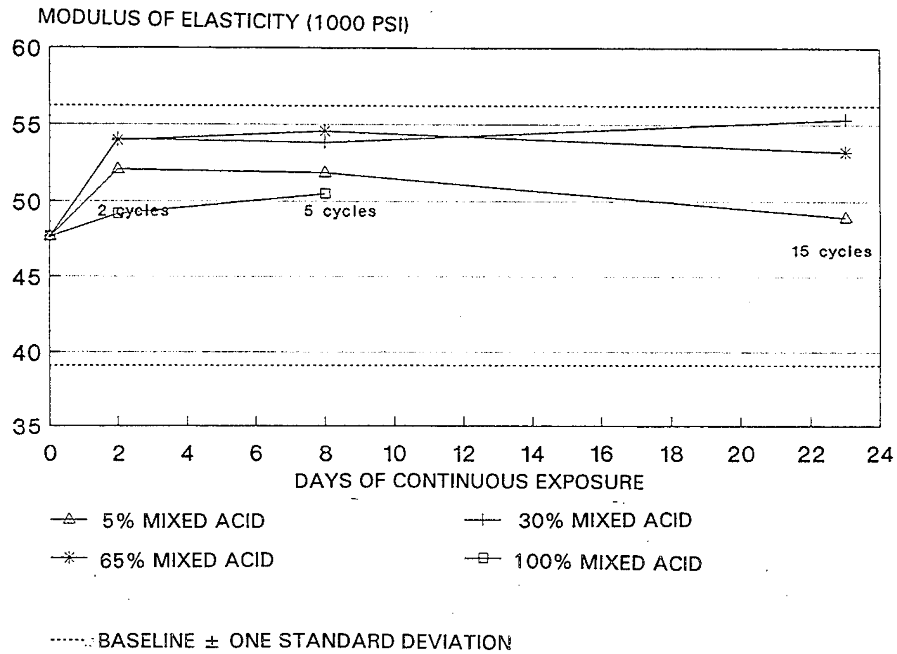


FIGURE 4. MODULUS OF ELASTICITY OF HDPE SAMPLES

Yield Stress and Yield Strain: Figures 5 and 6 show the yield stress and yield strain, respectively, for the exposed HDPE samples. The data show that 100% mixed acid has a profound effect on the yield stress and yield strain at some time after 48 hours of exposure. The yield stress and yield strain both begin much earlier. The polymer structure begins to yield, or become damaged, from a lower applied force and at dramatically lower elongation.

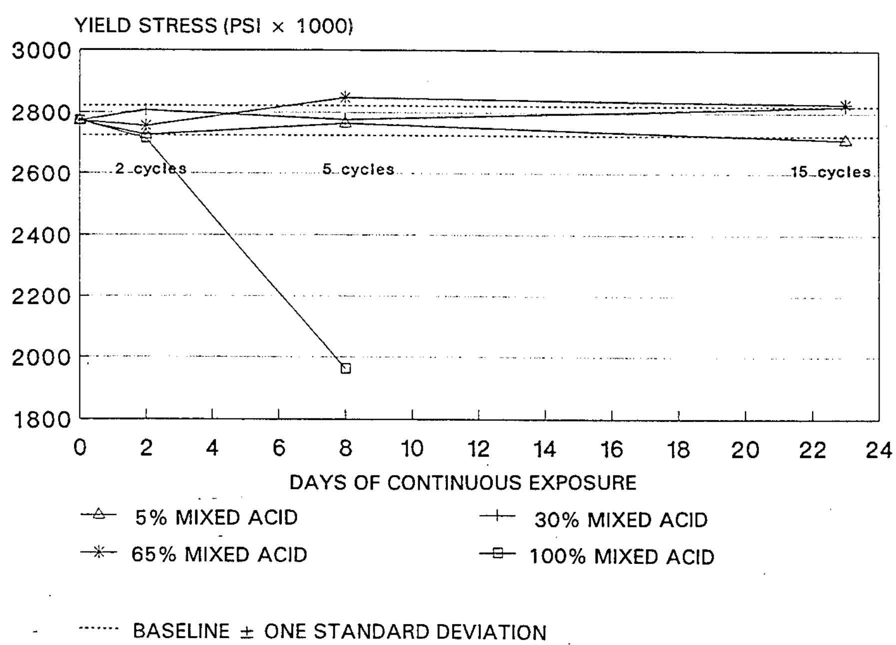


FIGURE 5. YIELD STRESS OF EXPOSED HDPE SAMPLES

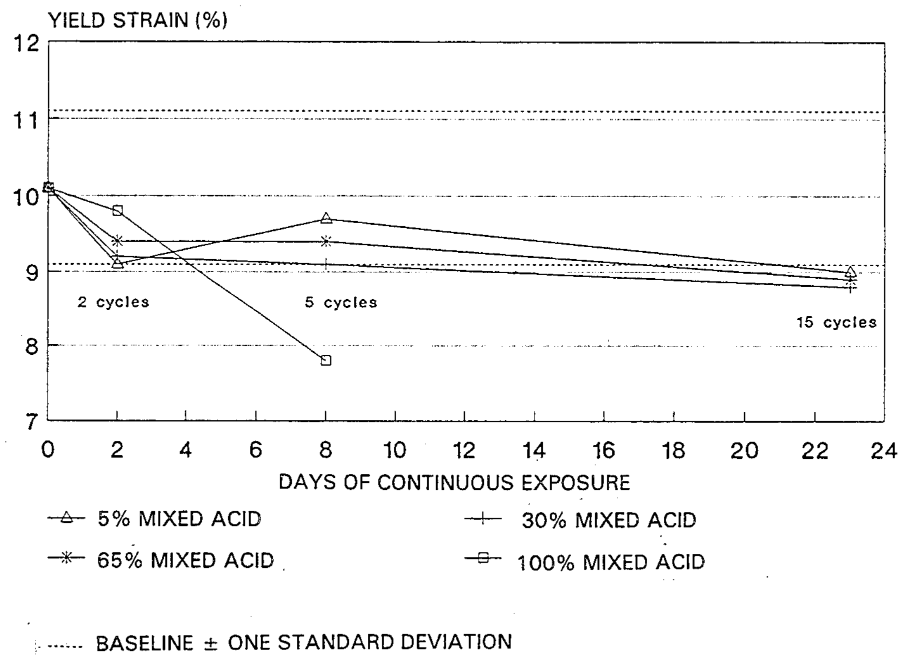


FIGURE 6. YIELD STRAIN OF EXPOSED HDPE SAMPLES

There is also a slight decrease in the yield strain of the samples from each of the other solutions (5%, 30%, and 65%) after 23 days of exposure. This decrease is statistically inconclusive however. These data points lie outside of one standard deviation of the unexposed sample, but when the standard deviation of the exposed samples is accounted for, they could, in reality, fall within the statistical range of "no effect." (The standard deviations for the exposed samples are not shown.) Standard deviations for these three solutions show that the errors would overlap, while the 100% solution does show a conclusive decrease in yield strain.

Maximum Stress and Maximum Strain: Figures 7 and 8 show the maximum stress and maximum strain, respectively, for the exposed HDPE samples. The data show that the 100% mixed acid and the 65% mixed acid have affected these properties.

The 100% mixed acid solution has again shown a profound effect on both the maximum stress and maximum strain at some time after 48 hours of exposure. These data, taken with the yield point data, indicate that pure mixed acid will severely deteriorate the HDPE over a relatively short exposure time, but that the liner should withstand the 48 hours exposure criteria for the dike.

It is also worth mentioning that the tensile properties were run approximately 10 days after the two-day exposure samples were withdrawn. This would seem to indicate that if the liner is properly washed and rinsed after it has been exposed to pure acid, decomposition of the HDPE may be prevented.

The exposure of the HDPE to the 65% mixed acid solution also has resulted in a gradual decrease in both the maximum stress and maximum strain over the 23 days of exposure. It is difficult to say if this trend would continue if exposure time was extended; but it is also unlikely that under normal care the HDPE dike will be exposed to this acid concentration for this duration.

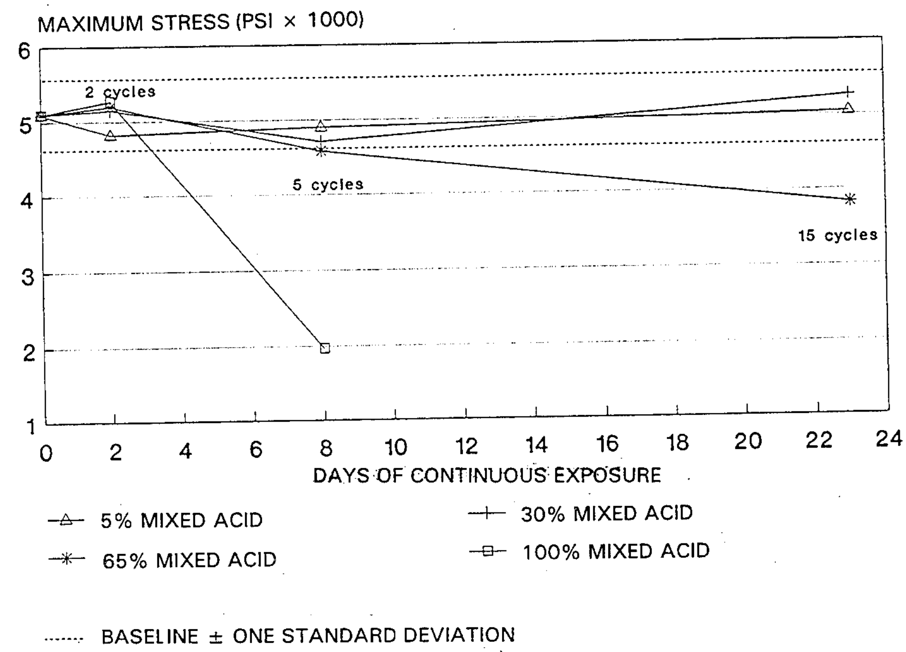


FIGURE 7. MAXIMUM STRESS OF EXPOSED HDPE SAMPLES

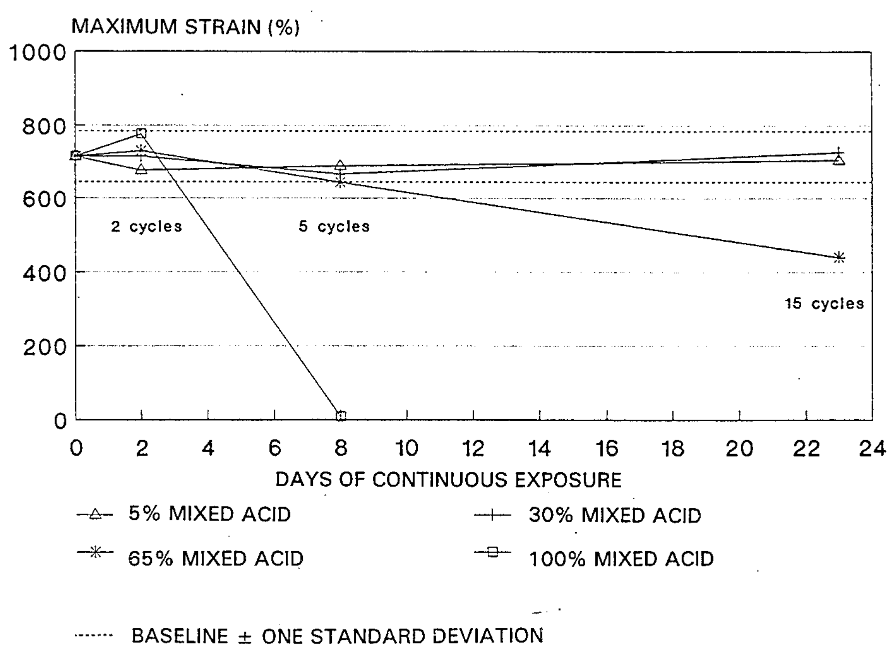


FIGURE 8. MAXIMUM STRAIN OF EXPOSED HDPE SAMPLES

DISCUSSION

The weight gain of the HDPE after exposure to the 100% mixed acid (Figure 2) indicates that either:

- Some acid is either absorbed into the HDPE structure, subsequently destroying the HDPE, or alternately,
- A reaction is taking place between the HDPE and the acid, resulting in a slightly different chemical structure with lower tensile properties.

In either case the tensile properties of the HDPE exposed to the 100% acid solution are diminished some time after 48 hours of direct, continuous immersion.

The HDPE samples were not tested immediately for tensile properties as originally planned due to scheduling conflicts. However, even though about 10 days elapsed between the time the two-day samples were withdrawn and the time the samples were tested, there appeared to be no adverse effects due to this waiting period. A weight gain after two days of exposure to 100% mixed acid was seen; therefore, it is not likely that a chemical reaction had yet taken place.

It is more likely that some acid was absorbed into the HDPE, resulting in a weight gain, but not enough was absorbed to cause destruction of the HDPE. After immersion was continued to the eight-day samples, destruction had taken place. There is no data between two days and eight days to show when the threshold exposure time occurs.

We also cannot conclude if the acid absorbed (weight gain) causes destruction or if destruction is caused mainly by exterior exposure. Exterior exposure seems to be the principal cause, though, since the period between two days and eight days yielded only a slight increase in weight, while the tensile properties were diminished considerably.

HDPE does expand and contract with changes in temperature; its coefficient of linear expansion is $1.2 \cdot 10^{-4}$/ °C. A 130 °F temperature change (e.g., from summer to winter temperature) will result in a 0.86% elongation, or strain. Table I shows that the yield strain is much higher than the thermal expansion strain, even after immersion for all samples tested. Therefore, even when subjected to any of the conditions of this study, the HDPE used for the actual dike lining will not reach its yield point (or point of some polymer destruction) due to changes in outdoor temperature.

EXPERIMENTAL ERRORS

Experimental errors are identified and discussed in the following paragraphs. Appendix E provides the data and calculations for the error estimations.

Sample Dimension Measurement:

The rectangular HDPE samples immersed in the acid were cut on a guillotine using a square guide. The measurement errors for length and width are due to imprecise square corners on the samples plus the micrometer error. The error for these measurements are 2.2% and 2.5%, respectively, based on the average standard deviation of measurements of several samples.

The error for the thickness measurements relates to the ability of the manufacturer to produce a sheet of HDPE of uniform thickness plus the micrometer error. The error for thickness is 0.2%, also based on the average standard deviation of measurements of several samples.

Note that the die-cut "dumbbell" samples used for tensile property testing were cut from the rectangular samples *after* immersion rather than prior to immersion to prevent deformation of the die-cut samples' dimensions during immersion.

Scale Accuracy:

HDPE samples were weighed before and after immersion to determine whether samples were being decomposed by the acid or whether acid was being absorbed into the HDPE. The scale resolution was 0.1 gram; therefore, the error is 0.05 gram. In most cases the weight remained constant or increased by 0.1 gram. For increases of this magnitude (0.35%) a scale with higher resolution would yield more accurate figures.

Acid Absorption Offset by HDPE Decomposition:

It is likely that in some cases acid absorption by the HDPE (causing a weight increase) was offset by HDPE decomposition (causing a weight decrease). The sample weight increased more often than it decreased; but there was a change in the color of the acid solutions, particularly the higher concentrations, indicating decomposition was taking place.

In estimating the magnitude of this error, I noted that in many cases the weight change was zero and only slight color changes were noted. It is assumed then that the magnitude of this error does not exceed the scale accuracy. In other words, I would not expect greater than a 0.05-gram weight increase or decrease. This error was then added to the scale accuracy error to calculate the total weight change error.

Room Temperature Variation:

Room temperature was not consistent when "before" and "after" size measurements were determined. The maximum variation in room temperature was 7.5 °C, which corresponds to an error of 0.14%, calculated from manufacturer specifications.

Acid Composition Change:

Vapor pressure differences of the components in the acid solutions may cause the acid composition to change slightly over time since the test containers were not tightly sealed. This is particularly true with solution 1, where heavy NO_x fumes were observed during the high temperature periods. This should be a negligible error, however, since no acid level change was noted in the containers.

Tensile Properties Testing Delay:

There was a delay of up to ten days from the time the samples were withdrawn from the acid until the time the tensile properties were tested. If acid was indeed absorbed into the polymer structure, it is likely that further HDPE decomposition was taking place as the samples awaited testing.

CONCLUSIONS

Conclusions generated from this study of the compatibility of HDPE with mixed nitrating acid are summarized below:

- The HDPE liner is sufficient to contain a mixed acid spill for 48 hours without serious adverse effects. After 48 hours the spill could at least be diluted to a level no longer destructive to the liner and thereby be contained within the containment dike.

- HDPE samples immersed in 100% mixed acid will experience a weight gain after 48 hours of continuous immersion. It is inconclusive whether the weight gain is attributed to acid absorption or chemical reaction between HDPE and the acid.

- It is suspected, but not conclusively proven, that the weight gain is due to acid absorption. Mere acid absorption does not appear to affect the properties of the HDPE if it is removed from the acid.

- Long periods of acid exposure seem to be the principal cause of diminishing tensile properties, rather than acid absorption, since long exposure times yield slight increases in weight, but considerably poorer tensile properties.

- HDPE should be capable of withstanding any concentration of mixed nitrating acid generated from an initial concentration of 53% sulfuric acid and 47% nitric acid for at least 48 hours with no adverse effects on tensile properties. However, greater than 48 hours of continuous exposure to 100% mixed acid will drastically diminish the tensile properties.

- Thermal expansion of the HDPE in the dike lining may cause up to 0.86% elongation or strain. This is a factor of nine times lower than the lowest yield strain obtained in this study (100% acid for 8 days). The yield strain indicates how far the material can be stretched before the polymer chains begin to break.

RECOMMENDATIONS

Based on the results of this study, HDPE should be suitable for use as secondary containment for mixed nitrating acid storage. A periodic maintenance contract is recommended due to physical abuse and continual exposure to various acid concentrations.

The following additional studies to answer outstanding questions regarding the chemical resistance to HDPE would be beneficial:

- Collect data between two days of exposure and eight days of exposure to determine when the threshold exposure time occurs.
- Test some samples after removal from the acid immediately while delaying testing of others. This would determine if acid absorbed into the HDPE causes destruction or if the destruction is caused primarily by direct immersion.
- Determine the effects of temperature on the chemical resistance by maintaining the immersed samples at constant temperature rather than cycling the temperature through extremes.
- Test other types of geomembrane and geotextile liners. Note in Appendix A that the Hypalon sample also passed the preliminary screening. This sample was not tested further because the HDPE was thicker and more rigid and appeared to be capable of withstanding more physical abuse. However, given more testing time, other lining materials may have shown equal or better chemical resistance without the potential installation and maintenance problems associated with HDPE.

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Appendix A

PRELIMINARY MATERIALS TESTING RESULTS

MIXED ACID CHEMICAL RESISTANCE STUDY
MATERIAL TESTING RESULTS

Sample Name	Liner Type	Test Length	Results/Comments
Overkote	Resin	24 hrs	Total destruction, completely dissolve
Overkote Plus	Resin	24 hrs	Total destruction, completely dissolve
DOW Silastic 732	Caulk	4 days	Sample nearly intact but exposed surface cracked
DOW Silastic 730	Caulk	4 days	Very small cracks in exposed surface; Sample intack below exposed surface
Hetron	Resin	4 days	Outer surface dissolved; bubbles form
Permagile	Caulk	4 days	Sample floated; sample bubbled until acid no longer in contact with sample
FX 571 Fox Ind.	Caulk	10 min	Sample dissolved
Essex Polyurethane	Poly- urethane	10 min	Sample dissolved
Morton Thiokol FE 1402	Caulk	10 min	Sample dissolved
Morton Thiokol FE 1407	Caulk	15 min	Sample dissolved
KOCH Permanite	Resin Polymer	3 days	All outer polymer dissolved; only cement base left
Pecora Synthacalk	Caulk	10 min	Sample dissolved
Morton Thiokol FE 2000	Caulk	15 min	Sample dissolved
Fabrico PVC Type 651	Liner	4 days	Sample hardened and curled but still intact
Fabrico PVC Type BOEE	Liner	4 days	Sample hardened and curled but still intact
Fabrico PVC Type 3134	Liner	4 days	Sample hardened and curled but still intact
HDPE SLT & Serrot	Liner	4 days	Not affected visually
Life Science 3510	Resin	2 min	Caused violent acid fume-off
Life Science 3116	Resin	3 days	Crust layer on acid; corrosion effect gradually increasing through sample
Hypalon	Liner	3 days	Not affected visually

HDPE Testing; FormTool; hdpe_r-2

Appendix B

MATERIAL COMPATIBILITY TESTING RESULTS

MATERIAL COMPATABILITY TESTING

Sample Number	Weight Bef.	Weight Aft.	Length Bef.	Length Aft.	Width Bef.	Width Aft.	Thickness Bef.	Thickness Aft.	Leachate	Exposures
01									No Exposure	0
02									"	0
03									"	0
04									"	0
05									"	0
06									"	0
07	14.6	14.8	5.895	5.908	1.973	1.972	0.084	0.082	100% PGDN	5 BLACK STICKY RESIDUE
08	14.2		5.851		1.980		0.081		"	11
09	15.2	15.4	5.900	5.918	2.020	2.021	0.081	0.078	100% PGDN	5
10	13.4	13.6	5.408	5.435	2.024	2.020	0.084	0.081	"	5
11	13.6	13.7	5.407	5.440	1.971	1.973	0.082	0.079	"	5 PATCHES OF RESIDUE
12	14.1		5.438		1.950		0.086		"	H
13	15.6	16.0	5.448	5.464	2.165	2.164	0.088	0.087	"	5
14	15.2	15.6	5.493	5.523	2.077	2.078	0.083	0.081	"	5 WARTS
15	15.6	16.0	6.011	6.022	2.040	2.035	0.094	0.094	"	2
16	16.6	16.7	6.072	6.072	2.179	2.191	0.083	0.083	"	2
17	13.8	14.0	5.369	5.389	2.020	2.026	0.076	0.077	"	2
18	14.1	14.3	5.381	5.396	1.928	1.937	0.087	0.087	"	2
19	13.5	13.7	5.373	5.384	1.923	1.924	0.083	0.084	"	2
20	13.6		5.401		1.989		0.080		"	11
21	13.6		5.338		1.988		0.082		"	11
22	13.0		5.389		1.970		0.080		"	11
23	14.7		5.906		2.009		0.069		"	11
24	14.5	14.7	5.841	5.852	1.988	1.992	0.079	0.080	"	2
25	15.2	15.2	5.918	5.930	1.971	1.978	0.093	0.091	65% PGDN	2
26	14.7	14.7	5.892	5.882	1.950	1.960	0.071	0.073	"	2
27	14.8	14.9	6.043	6.063	1.970	1.981	0.084	0.084	"	15
28	16.2	16.3	5.885	5.900	2.146	2.145	0.089	0.090	"	15
29	14.8	14.8	6.019	6.021	1.962	1.967	0.084	0.084	"	15
30	15.6	15.7	5.518	5.538	2.084	2.091	0.088	0.089	"	5
31	15.0	15.1	5.543	5.573	2.118	2.123	0.080	0.081	"	15
32	14.3	14.4	5.569	5.591	1.926	1.926	0.085	0.084	"	15
33	16.1	16.2	5.844	5.880	2.110	2.114	0.082	0.083	"	15
34	14.4	14.5	5.532	5.555	2.109	2.114	0.081	0.081	"	2
35	15.0	15.1	5.972	6.004	1.955	1.960	0.082	0.082	"	2
36	13.0	12.9	5.236	5.269	1.956	1.966	0.082	0.082	"	2
37	15.0	15.0	5.848	5.886	1.953	1.962	0.077	0.078	"	5
38	14.2	14.2	5.448	5.465	1.946	1.952	0.081	0.082	"	5
39	13.1	13.1	5.328	5.351	1.958	1.967	0.081	0.081	"	5
40	16.3	16.4	6.003	6.003	2.065	2.070	0.084	0.084	"	5
41	14.7	14.8	6.025	6.038	1.907	1.919	0.082	0.082	"	5 deformed reshaped
42	14.7	14.8	5.947	5.990	1.988	1.987	0.084	0.083	"	2
43	15.1	15.2	5.710	5.724	1.966	1.969	0.094	0.096	30% PGDN	15
44	14.1	14.1	5.856	5.870	1.971	1.978	0.070	0.073	"	15
45	17.1	17.2	5.929	5.946	2.170	2.175	0.091	0.092	"	15
46	15.8	15.8	5.861	5.878	2.126	2.133	0.076	0.070	"	15
47	14.6	14.6	5.823	5.837	1.950	1.952	0.090	0.092	"	5 small warts
48	14.3	14.3	5.419	5.430	2.162	2.167	0.081	0.081	"	5
49	15.2	15.2	5.485	5.482	2.087	2.087	0.086	0.085	"	5
50	13.2	13.3	5.444	5.441	1.971	1.979	0.071	0.071	"	2
51	14.1	14.2	5.291	5.308	2.132	2.140	0.076	0.072	"	2
52	13.6	13.7	5.352	5.374	2.023	2.028	0.076	0.072	"	2
53	14.0	14.0	5.364	5.380	2.061	2.067	0.076	0.074	"	15

Measurements taken at corner of sample with sample no.

Facilities and Equipment; Formtool; HDPE_1

MATERIAL COMPATABILITY TESTING

Sample Number	Weight Bef.	Weight Aft.	Length Bef.	Length Aft.	Width Bef.	Width Aft.	Thickness Bef.	Thickness Aft.	Leachate	
54	13.8	13.9	5.263	5.282	2.029	2.030	0.090	0.093	30% PEDH	15
55	13.2	13.2	5.239	5.259	1.956	1.963	0.095	0.099	"	5
56	15.9	15.9	5.892	5.909	2.062	2.072	0.090	0.088	"	2
57	15.1	15.2	5.898	5.905	2.031	2.034	0.088	0.089	"	2
58	16.1	16.2	5.981	6.007	2.113	2.118	0.097	0.091	"	2
59	14.9	15.0	5.936	5.948	1.957	1.958	0.092	0.091	"	5
60	15.6	15.6	6.034	6.049	2.020	2.024	0.082	0.081	"	5
61	15.0	15.0	6.072	>6.073	1.954	1.953	0.084	0.084	5% PEDH	15
62	13.8	13.8	5.233	5.236	1.989	1.990	0.086	0.083	"	15
63	13.5	13.5	5.295	5.307	1.968	1.970	0.083	0.082	"	15
64	13.6	13.6	5.343	5.352	2.084	2.089	0.080	0.079	"	5
65	13.9	13.9	5.480	5.493	2.008	2.012	0.082	0.081	"	5
66	13.5	13.5	5.358	5.369	1.921	1.925	0.084	0.084	"	2
67	14.5	14.5	5.245	5.251	1.984	1.985	0.087	0.086	"	5
68	14.2	14.3	5.266	5.275	2.067	2.072	0.086	0.086	"	2
69	13.1	13.1	5.221	5.224	1.946	1.950	0.083	0.083	"	2
70	14.~~8~~5	14.5	5.196	5.204	2.160	2.164	0.094	0.093	"	5 warts on 1 side
71	14.2	14.2	5.180	5.191	2.086	2.090	0.099	0.094	"	15
72	12.7	12.7	5.188	5.182	1.959	1.961	0.089	0.093	"	15
73	13.6	13.6	5.180	5.190	2.029	2.030	0.076	0.075	"	5
74	15.1	15.2	5.995	6.029	1.957	1.965	0.076	0.076	"	deformed ~ but reshaped 2
75	13.2	13.2	5.323	5.345	1.904	1.910	0.090	0.092	"	2
76	13.4	13.4	5.255	5.279	1.959	1.965	0.087	0.095	"	2
77	14.1	14.1	5.277	5.289	1.910	1.908	0.092	0.092	"	5
78	13.4	13.4	5.332	5.345	1.965	1.967	0.074	0.077	"	15

Ø cycle = room temp was cold especially for 2nd half of samples
2 cycles = room temp when measuring = 16.5 °C
5 cycles = " " " " = 13.0 °C
15 " " " " " ~~[illegible]~~ ~~[illegible]~~ 12.5 °C

Errors = shape of samples (curvature)
measuring temp
evaporation
AL until tensile prop
Measure same place

Measurements taken at corner of sample with sample no.

Facilities and Equipment; Formtool; HDPE_1

HDPE Test Plan

Acid Solutions: 100% PEDN Mixed Acid
65% PEDN Mixed Acid
30% PEDN Mixed Acid
5% PEDN Mixed Acid

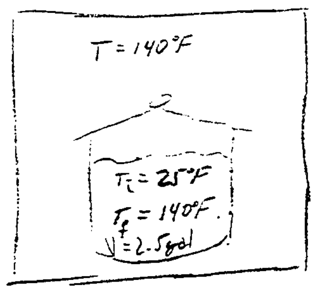
Tests: Dimensions: taken at 1 corner
Weight: on lab scale
Specific Gravity: calculated
Tensile Properties: 6 ea/cycle/solution

Cycles: Ø cycles: nonexposure
2 cycles
5 cycles
15 cycles

Temperature: Ambient - 120°F through 5 cycles (49°C)
Ambient - 140°F 5-15 cycles (60°C)

Samples: 18 samples per solution
6 samples nonexposure
78 samples total

HDPE Testing | Cycle Time



		HNO_3	H_2SO_4	H_2O
k	Btu/ft·h·°F		0.21	0.35
C_p	Btu/lb·°F		0.35	1.0
ρ		1.4	1.83	1.0

Conduction: Assume sphere

$$t_T = \frac{r_m^2}{9.87\alpha} \ln \frac{0.608\,(T_s - T_o)}{T_s - \bar{T}_b} \qquad \alpha = \frac{k}{\rho C_p}$$

$$t_T = \frac{(7in)^2\left(\frac{1ft}{12in}\right)^2}{9.87(0.005588\ ft^2/hr)} \ln\left[\frac{0.608(140-25)}{140-135}\right] \qquad \alpha = \frac{0.21\ Btu/ft\cdot h\cdot°F}{(1.72)(8.345\ lb/gal)(0.35\ Btu/lb\cdot°F)\left(\frac{7.4805\ gal}{ft^3}\right)}$$

$$= 0.005588\ ft^2/hr$$

$$= 16.3\ hr$$

Convection:

$$q = hA\,(T_h - \bar{T}_b) \qquad A = \pi r^2 + \pi d L$$

$$= \left(0.2\ Btu/ft^2\cdot h\cdot°F\right)(2.01 ft^2)(140-135) \qquad = \pi(4.5in)^2 + \pi(9)(8) = 290\ in^2 = 2.01\ ft^2$$

$$= 2.0126\ Btu/hr$$

$$t = 1{,}444/2.0126 = 717.6\ hr$$

$$q = m c_p \Delta T$$

$$q = (35.88\ lb)(0.35\ Btu/lb\cdot°F)(140-25)$$

$$= 1{,}444\ Btu \qquad (120-25)$$

1193

Radiation: $q = \sigma \varepsilon_w A\,(T_w^4 - T^4)$

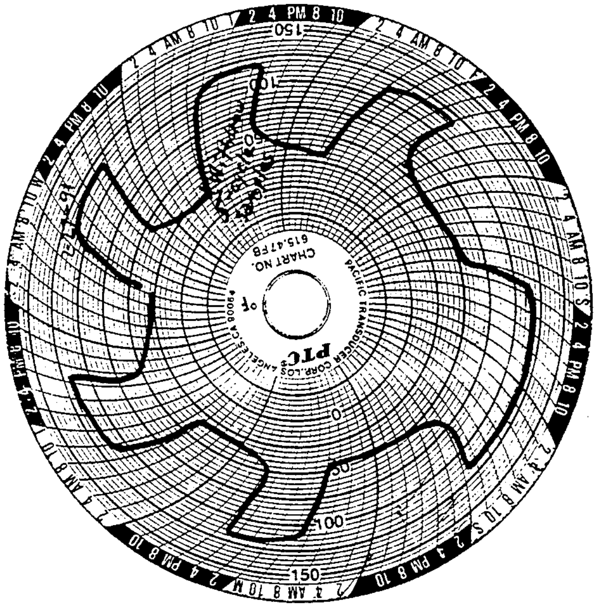
T_w = surface Temp
T = surroundings temp

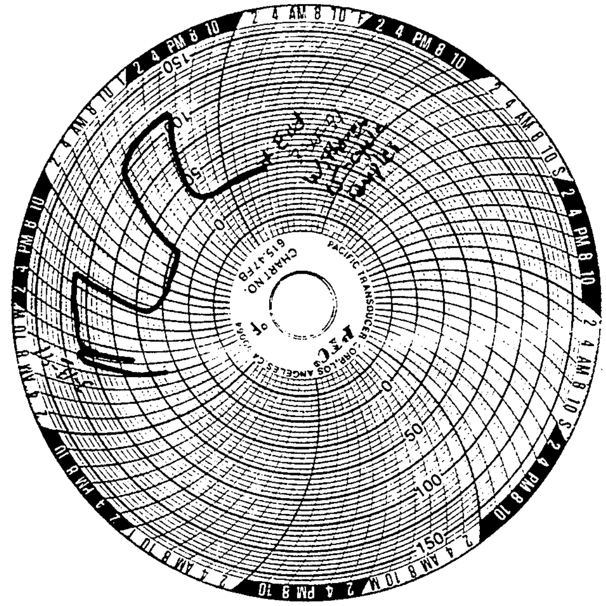
$$q = 0.1713\cdot10^{-8}\ \frac{Btu}{ft^2\cdot h\cdot R^4}\,(0.88)(2.01\ ft^2)(485^4 - 600^4)$$

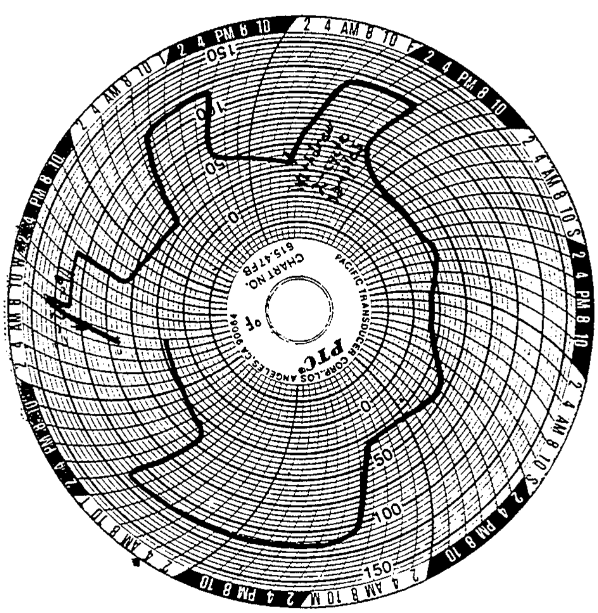
Black paint on steel

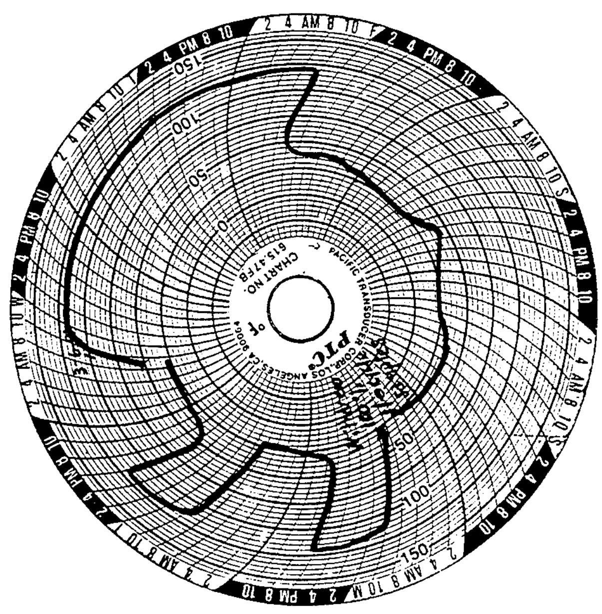
$$= -225.0\ Btu/h \qquad -175.23\ Btu/h \qquad (485^4 - 580^4)$$

$$t = 1{,}444/225 = 6\ hrs \qquad = 6.81\ hrs$$









HDPE Testing | Acid Preparation | 2-19-91

65 % PGDN Mixed Acid

$$\% = \frac{M.A.}{M.A. + H_2O} = 0.65$$

$$M.A. = .65 M.A. + .65 H_2O$$

$$.35\ MA = .65\ H_2O$$

$$MA = 1.857143\ H_2O$$

Water	$Acid_{th}$	$ACID_{act}$
~~450.0~~		
~~449.9~~		
450.0	835.7	836.5
463.0	859.9	868.1

Bright red-orange and hot. Alot of NOx formed

30% PGDN Mixed Acid

$$.30 = \frac{MA}{MA + H_2O}$$

$$MA = .30 MA + .30 H_2O$$

$$.70 MA = .30\ H_2O$$

$$MA = 0.428571\ H_2O$$

Water	$Acid_{th}$	$Acid_{act}$
792.0	339.4	~~34~~ 341.7
516.5	221.4	222.2

5% PGDN Mixed Acid

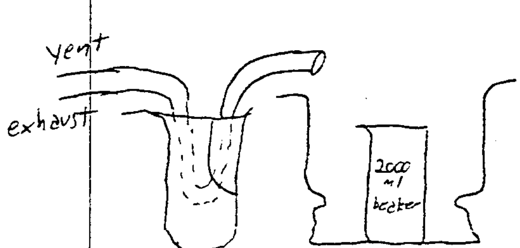
$$.05 = \frac{MA}{MA + H_2O}$$

$$MA = .05 MA + .05 H_2O$$

$$.95 MA = .05\ H_2O$$

$$MA = 0.052632\ H_2O$$

Water	$Acid_{th}$	$Acid_{act}$
812.0	42.7	46.4
575.1	26.6	27.8



Room Temp = 58°F

HDPE Testing | Sample Immersion | 2-20-91

2-20-91 Begin testing

100% PGDN in square desiccator # 07-24
Temp =
0921 when immersed

0735 All samples in solution and oven turned on
set on 69°C initially

100% some floating on top of others -- not all immersed but ones that are are completely immersed

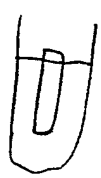
65%

slightly over half way

30%

3/4 of way

5%



almost all the way -- just corners sticking out

HDPE Testing | Temperature Cycling | I

After in oven since this A.M. set at 49°C

		100%	65%	30%	5%
2-20-91	1730	46°C	46°C	46°C	46°C

W Set oven to 55°C for tomorrow
No change appearing in samples
Brought to flammable locker

I 2-21-91	0845	7°C	7°C	8°C	7°C

complete R Turned samples over so floating ones on bottom — flipped samples vertically

All samples floating ~ same as yesterday

52°C 51°C

1726 Put outside in locker

2 2-22-91 0855 - 0930
F

Withdrew 6 samples from each solution
1 F.W. wash
1 S.W. wash
1 F.W. wash
oven to dry

flipped all samples in solution & put in oven ~0915

1815 Took samples outside in locker

3 2-25-91 0930 - 0945
M
Flipped samples over and put in oven @ 55°C

Forgot to take samples out in P.M.

2-26-91 1350
Samples out of oven to locker
NO_x fumes in 100% container - 100% solution was dark brown-black; samples 'decomposing' slightly ??
samples appeared to be intact

HDPE Testing | Temperature Cycling | 2

4 2-27-91 ~1100
Samples into oven
100% solution dark brown
changed temp chart

1935
Samples into locker
More NO_x fumes above 100% solution

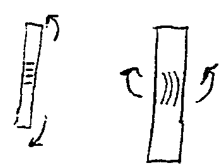
5 2-28-91 0900
6 samples withdrawn
remaining samples flipped back in oven

Ventilation Not work

Washes = FW
SW
FW

In 100% samples = when bent, surface would crack

Didn't happen in 5% 30% (5%)



also black, sometimes obvious patches or spots, residue. It was stick and would wipe off on towel with some ~~effort~~

5% samples still had yellow grease pencil markings on them
30% samples " " " " - - - - - - - - - - -

when surface cracked, it became sticky, like acid was absorbed into material

2-28-91 1705 samples to locker

6 3-1-91 Samples to oven 0800
flipped over

* Might want to ↑ temp

3-1-91 1622 Remove from oven
NO_x in 100%

HDPE Testing | Temperature Cycling | 3

7 3-2-91 Sat ~1300
Flipped samples & put into oven 55°C

3-3-91 Sun 1115
Samples to locker
Black residue forming on side of desiccator in 100% solution; forming ~~at top~~ at level of top of acid solution
Alot of NO_x fumes over 100% solution

8 3-4-91 0850
Samples into oven 55°C

3-4-91 1735
Samples to locker
Dark NO_x fumes over 100% solution

9 3-5-91 0900
Samples into oven 55°C

1920 Samples to locker
100% - NO_x fumes

10 3-6-91 0910
Samples into oven 55°C — Went on Travel & Forgot To Take them out

3-8-91 0900
Samples out of oven
Thick NO_x over 100%

11 3-11-91 Mon 0900

100% samples broken down
brittle chunks that broke on touch
removed, neutralized, and discarded

others flipped and into oven

3-11-91 1810
Samples to locker

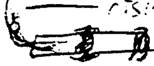
12 3-12-91 0850
Samples into oven

3-12-91 1710
Samples out to locker

Put Epoxy Samples in (NOTE for tomorrow)

13 3-13-91 0920
Samples into oven

Epoxy samples

100%	65%	30%	5%
0-8 g (floated) After a few minutes ~~#~~ surface appeared bubbly & bloated	white milky liquid & bubbles rising from open end 	No effect noticed	No effect noticed

No samples fumed

11~~00~~ - 100% sample dissolved (Epoxy)

Alot of NO_x in 65% & 30%
Steel in 65% bubbling

Moved to 502 1100-1130

1950 Samples to locker

14 0850 Samples to oven 3-14-91
1720 Samples to locker

15 0900 All samples out 3-15-91
~~#~~ Samples from each sol'n still had grease pencil marks

Appendix C

PHYSICAL PROPERTY DATA

HDPE TESTING IN ACID SOLUTIONS
WEIGHT/DIMENSIONS DATA BEFORE AND AFTER
HDPE Testing; quattro; hdpe-2

Sample Number	Exposures	Acid Concent.	Weight Before	Weight After	% Weight Change	Length Before	Length After	Width Before	Width After	% Width Change	Thick. Before	Thick After	Volume Before	Volume After
1	0	0												
2	0	0												
3	0	0												
4	0	0												
5	0	0												
6	0	0												
66	2	5	13.5	13.5	0	5.358	5.369	1.921	1.925	0.208225	0.084	0.084	0.864588	0.868167
68	2	5	14.2	14.3	0.704225	5.266	5.275	2.067	2.072	0.241896	0.086	0.086	0.936095	0.939963
69	2	5	13.1	13.1	0	5.221	5.224	1.946	1.950	0.20555	0.083	0.083	0.843285	0.845504
74	2	5	15.1	15.2	0.662252	5.995	6.029	1.957	1.965	0.408789	0.076	0.076	0.891648	0.900371
75	2	5	13.2	13.2	0	5.323	5.345	1.904	1.910	0.315126	0.090	0.092	0.912149	0.939223
76	2	5	13.4	13.4	0	5.255	5.279	1.959	1.965	0.306279	0.087	0.095	0.895625	0.985457
Average:			13.75	13.78333	0.227746	5.403	5.420167	1.959	1.9645	0.280977	0.084333	0.086	0.890565	0.913114
Standard Deviation:			0.699405	0.742556	0.32231	0.268541	0.276414	0.052131	0.052118	0.071475	0.004346	0.006191	0.03021	0.04724
64	5	5	13.6	13.6	0	5.343	5.352	2.084	2.089	0.239923	0.080	0.079	0.890785	0.883246
65	5	5	13.9	13.9	0	5.480	5.493	2.008	2.012	0.199203	0.082	0.081	0.902315	0.895205
67	5	5	14.5	14.5	0	5.245	5.251	1.984	1.985	0.050403	0.087	0.086	0.905329	0.896398
70	5	5	14.5	14.5	0	5.196	5.204	2.160	2.164	0.185185	0.094	0.093	1.054996	1.047315
73	5	5	13.6	13.6	0	5.180	5.190	2.029	2.030	0.049285	0.076	0.075	0.798777	0.790177
77	5	5	14.1	14.1	0	5.277	5.289	1.910	1.908	-0.10471	0.092	0.092	0.927274	0.92841
Average:			14.03333	14.03333	0	5.286833	5.2965	2.029167	2.031333	0.103215	0.085167	0.084333	0.913246	0.906792
Standard Deviation:			0.372678	0.372678	0	0.101636	0.103051	0.078329	0.08027	0.118006	0.00644	0.006625	0.075365	0.075949
61	15	5	15.0	15.0	0	6.072		1.954	1.953	-0.05118	0.084	0.084	0.996634	.
62	15	5	13.8	13.8	0	5.233	5.236	1.989	1.990	0.050277	0.086	0.083	0.895126	0.86483
63	15	5	13.5	13.5	0	5.295	5.307	1.968	1.970	0.101626	0.083	0.082	0.864906	0.857293
71	15	5	14.2	14.2	0	5.180	5.191	2.086	2.090	0.191755	0.099	0.094	1.069743	1.019824
72	15	5	12.7	12.7	0	5.188	5.182	1.959	1.961	0.102093	0.089	0.093	0.904533	0.945057
78	15	5	13.4	13.4	0	5.332	5.345	1.965	1.967	0.101781	0.074	0.077	0.775326	0.809548
Average:			13.76667	13.76667	0	5.383333	5.2522	1.986833	1.9885	0.082726	0.085833	0.0855	0.917711	0.89931
Standard Deviation:			0.713364	0.713364	0	0.31273	0.064111	0.045685	0.046772	0.07299	0.00747	0.006076	0.094064	0.074334
50	2	30	13.2	13.3	0.757576	5.444	5.441	1.971	1.979	0.405885	0.071	0.071	0.761839	0.764509
51	2	30	14.1	14.2	0.70922	5.291	5.308	2.132	2.140	0.375235	0.076	0.072	0.857311	0.817857
52	2	30	13.6	13.7	0.735294	5.352	5.374	2.023	2.028	0.247158	0.076	0.072	0.822859	0.78469
56	2	30	15.9	15.9	0	5.892	5.909	2.062	2.072	0.484966	0.090	0.088	1.093437	1.077423
57	2	30	15.1	15.2	0.662252	5.898	5.905	2.031	2.034	0.14771	0.088	0.089	1.054138	1.068959
58	2	30	16.1	16.2	0.621118	5.981	6.007	2.113	2.118	0.23663	0.097	0.091	1.225872	1.157777
Average:			14.66667	14.75	0.58091	5.643	5.657333	2.055333	2.061833	0.316264	0.083	0.0805	0.969243	0.945203
Standard Deviation:			1.108553	1.090489	0.263691	0.285615	0.287534	0.054768	0.054998	0.115107	0.009238	0.008884	0.166064	0.159487
47	5	30	14.6	14.6	0	5.828	5.837	1.950	1.952	0.102564	0.090	0.092	1.022814	1.048232
48	5	30	14.3	14.3	0	5.419	5.430	2.162	2.167	0.231267	0.081	0.081	0.948986	0.953112
49	5	30	15.2	15.2	0	5.485	5.482	2.087	2.087	0	0.086	0.085	0.984459	0.972479
55	5	30	13.2	13.2	0	5.239	5.259	1.956	1.963	0.357873	0.095	0.099	0.973511	1.022018

% Volume Change	Sp. Gr. Before	Sp. Gr. After	% Sp. Gr. Change
0.413953	0.952847	0.948919	-0.41225
0.413218	0.925694	0.928377	0.28981
0.263128	0.947972	0.945484	-0.26244
0.978247	1.033433	1.030199	-0.31293
2.968168	0.883094	0.857638	-2.88261
10.03008	0.913014	0.829785	-9.11576
2.511132	0.942675	0.9234	-2.11603
3.486786	0.046702	0.065394	3.290434
-0.84634	0.931676	0.939628	0.853562
-0.78794	0.94006	0.947526	0.794196
-0.98646	0.977373	0.987111	0.996293
-0.72801	0.838718	0.844869	0.733345
-1.07655	1.038992	1.050299	1.088264
0.122452	0.927918	0.926783	-0.1223
-0.71714	0.942456	0.949369	0.723893
0.393372	0.060046	0.062102	0.396833
	0.918448		
-3.38449	0.940793	0.973749	3.503054
-0.88029	0.952497	0.960956	0.88811
-4.66642	0.810043	0.849693	4.894832
4.480091	0.856797	0.820058	-4.28799
4.413915	1.054676	1.010092	-4.22732
-0.00744	0.922209	0.92291	0.154137
3.83559	0.077119	0.074259	3.825122
0.350555	1.057328	1.061616	0.405599
-4.60214	1.003643	1.059522	5.567589
-4.63862	1.008584	1.065421	5.635314
-1.46455	0.887364	0.900554	1.486318
1.405963	0.874135	0.867724	-0.7334
-5.55479	0.801456	0.853864	6.539141
-2.41726	0.938752	0.968117	3.150094
2.668886	0.090198	0.095099	2.854475
2.485086	0.871074	0.849952	-2.42483
0.434726	0.919549	0.915569	-0.43284
-1.21685	0.942204	0.95381	1.231839
4.982718	0.827431	0.788159	-4.74623

59	5	30	14.9	15.0	0.671141	5.936	5.948	1.957	1.958	0.051099	0.092	0.091	1.068741	1.059803
60	5	30	15.6	15.6	0	6.034	6.049	2.020	2.024	0.19802	0.082	0.081	0.999472	0.991697
Average:			14.63333	14.65	0.111857	5.656833	5.6675	2.022	2.025167	0.156804	0.087667	0.088167	0.999664	1.00789
Standard Deviation:			0.763035	0.76974	0.250119	0.291594	0.291731	0.079156	0.079237	0.119983	0.005121	0.006491	0.038278	0.038813
43	15	30	15.1	15.2	0.662252	5.710	5.724	1.966	1.969	0.152594	0.094	0.096	1.055231	1.081973
44	15	30	14.1	14.1	0	5.856	5.870	1.971	1.978	0.35515	0.070	0.073	0.807952	0.847593
45	15	30	17.1	17.2	0.584795	5.929	5.946	2.170	2.175	0.230415	0.091	0.092	1.1708	1.189795
46	15	30	15.8	15.8	0	5.861	5.878	2.126	2.133	0.329257	0.076	0.070	0.946997	0.877644
53	15	30	14.0	14.0	0	5.364	5.380	2.061	2.067	0.291121	0.076	0.074	0.840196	0.822914
54	15	30	13.8	13.9	0.724638	5.263	5.282	2.029	2.030	0.049285	0.090	0.093	0.961076	0.997189
Average:			14.98333	15.03333	0.328614	5.663833	5.68	2.053833	2.058667	0.234637	0.082833	0.083	0.963709	0.969518
Standard Deviation:			1.176742	1.19257	0.331094	0.257816	0.257034	0.075218	0.075826	0.106279	0.009136	0.010801	0.123197	0.133375
25	2	65	15.2	15.2	0	5.918	5.930	1.971	1.978	0.35515	0.093	0.091	1.084787	1.067388
26	2	65	14.7	14.7	0	5.892	5.882	1.950	1.960	0.512821	0.071	0.073	0.815747	0.841597
34	2	65	14.4	14.5	0.694444	5.533	5.555	2.109	2.114	0.237079	0.081	0.081	0.945197	0.951205
35	2	65	15.0	15.1	0.666667	5.972	6.004	1.955	1.960	0.255754	0.082	0.082	0.957371	0.964963
36	2	65	13.0	12.9	-0.76923	5.236	5.269	1.956	1.966	0.511247	0.082	0.082	0.839813	0.849426
42	2	65	14.7	14.8	0.680272	5.947	5.990	1.988	1.987	-0.0503	0.084	0.083	0.993101	0.987877
Average:			14.5	14.53333	0.212025	5.749667	5.771667	1.988167	1.994167	0.303625	0.082167	0.082	0.939336	0.943743
Standard Deviation:			0.716473	0.767391	0.534081	0.27318	0.270342	0.055508	0.054468	0.192141	0.006414	0.005228	0.090908	0.078604
30	5	65	15.6	15.7	0.641026	5.518	5.538	2.084	2.091	0.335893	0.088	0.089	1.011957	1.030616
37	5	65	15.0	15.0	0	5.848	5.886	1.953	1.962	0.460829	0.077	0.078	0.879428	0.90077
38	5	65	14.2	14.2	0	5.448	5.465	1.946	1.952	0.308325	0.081	0.082	0.858746	0.87475
39	5	65	13.1	13.1	0	5.328	5.351	1.958	1.967	0.459653	0.081	0.081	0.84501	0.852559
40	5	65	16.3	16.4	0.613497	6.003	6.003	2.065	2.070	0.242131	0.084	0.084	1.04128	1.043802
41	5	65	14.7	14.8	0.680272	6.025	6.038	1.907	1.919	0.629261	0.082	0.082	0.942153	0.950128
Average:			14.81667	14.86667	0.322466	5.695	5.7135	1.9855	1.9935	0.406015	0.082167	0.082667	0.929763	0.942104
Standard Deviation:			1.015573	1.051454	0.323047	0.275136	0.271669	0.065265	0.063673	0.127174	0.003337	0.00335	0.075394	0.073603
27	15	65	14.8	14.9	0.675676	6.043	6.063	1.970	1.981	0.558376	0.084	0.084	0.999996	1.008907
28	15	65	16.2	16.3	0.617284	5.885	5.900	2.146	2.145	-0.0466	0.089	0.090	1.124	1.138995
29	15	65	14.8	14.8	0	6.019	6.021	1.962	1.967	0.254842	0.084	0.084	0.991979	0.994838
31	15	65	15.0	15.1	0.666667	5.543	5.573	2.118	2.123	0.236072	0.080	0.081	0.939206	0.95835
32	15	65	14.3	14.4	0.699301	5.569	5.591	1.926	1.926	0	0.085	0.084	0.911701	0.904534
33	15	65	16.1	16.2	0.621118	5.844	5.880	2.110	2.114	0.189573	0.082	0.083	1.011129	1.031717
Average:			15.2	15.28333	0.546674	5.817167	5.838	2.038667	2.042667	0.198711	0.084	0.084333	0.996335	1.006223
Standard Deviation:			0.704746	0.715115	0.24621	0.197405	0.191901	0.08774	0.08675	0.197337	0.002769	0.002749	0.067052	0.071935
16	2	100	16.6	16.7	0.60241	6.072		2.179	2.191	0.550711	0.083	0.083	1.098164	
15	2	100	15.6	16.0	2.564103	6.011	6.022	2.030	2.035	0.246305	0.094	0.094	1.147019	1.151948
17	2	100	13.8	14.0	1.449275	5.369	5.389	2.020	2.026	0.29703	0.076	0.077	0.824249	0.840695
18	2	100	14.1	14.3	1.41844	5.381	5.396	1.928	1.937	0.466805	0.087	0.087	0.902587	0.909329
19	2	100	13.5	13.7	1.481481	5.373	5.384	1.923	1.924	0.052002	0.082	0.084	0.847247	0.870141
24	2	100	14.5	14.7	1.37931	5.841	5.852	1.988	1.992	0.201207	0.079	0.080	0.917341	0.932575
Average:			14.68333	14.9	1.482503	5.6745	5.6086	2.011333	2.0175	0.302343	0.0835	0.084167	0.956101	0.940937
Standard Deviation:			1.085383	1.087811	0.571588	0.308041	0.2735	0.085467	0.087895	0.165732	0.005795	0.005398	0.122632	0.110141
7	5	100	14.6	14.8	1.369863	5.895	5.908	1.973	1.972	-0.05068	0.084	0.082	0.97699	0.955347
9	5	100	15.2	15.4	1.315789	5.900	5.918	2.020	2.021	0.049505	0.081	0.078	0.965358	0.932902
10	5	100	13.4	13.6	1.492537	5.408	5.435	2.024	2.020	-0.19763	0.084	0.081	0.919447	0.889275
11	5	100	13.6	13.7	0.735294	5.407	5.440	1.971	1.973	0.101471	0.082	0.079	0.87389	0.847916

-0.83635	0.850771	0.863704	1.520207
-0.77786	0.952473	0.95994	0.783959
0.845245	0.893917	0.888523	-0.67798
2.224513	0.046942	0.060925	2.246438

2.534283	0.873229	0.857286	-1.82576
4.906287	1.064957	1.015151	-4.67683
1.622393	0.891276	0.882176	-1.02103
-7.32344	1.01814	1.098595	7.90215
-2.05684	1.016826	1.038179	2.100033
3.75749	0.876234	0.850621	-2.92302
0.573362	0.956777	0.957001	-0.07408
4.146003	0.07835	0.097364	4.115294

-1.60391	0.855063	0.869001	1.630055
3.16877	1.099665	1.06589	-3.07144
0.635636	0.929692	0.930235	0.058437
0.792959	0.956114	0.954916	-0.1253
1.144722	0.944626	0.926751	-1.89229
-0.52609	0.90328	0.914235	1.212745
0.602014	0.948073	0.943504	-0.36463
1.475301	0.075335	0.060515	1.65145

1.843873	0.940722	0.929611	-1.18107
2.426783	1.040854	1.016193	-2.36929
1.863567	1.009072	0.990611	-1.82947
0.893319	0.946037	0.937661	-0.88541
0.242131	0.955254	0.958793	0.370469
0.846386	0.952126	0.950558	-0.16472
1.352676	0.974011	0.963905	-1.00991
0.747957	0.037458	0.030321	0.929532

0.891185	0.903155	0.901226	-0.21361
1.334103	0.879524	0.873302	-0.70738
0.288155	0.910454	0.907838	-0.28733
2.038305	0.974606	0.961505	-1.34424
-0.78607	0.957155	0.971485	1.497144
2.036108	0.971669	0.958194	-1.38675
0.966964	0.932761	0.928925	-0.40703
0.997104	0.03667	0.036595	0.966613

	0.922444		
0.429754	0.829952	0.84759	2.125215
1.995259	1.021691	1.016222	-0.5353
0.746865	0.953298	0.959653	0.666596
2.702125	0.97235	0.960793	-1.18853
1.660668	0.964575	0.961906	-0.27676
1.506934	0.944052	0.949233	0.158244
0.828082	0.058908	0.055175	1.149907

-2.21526	0.91193	0.945364	3.666346
-3.3621	0.960846	1.007358	4.840638
-3.28152	0.889359	0.933258	4.936035
-2.97219	0.949688	0.985976	3.821053

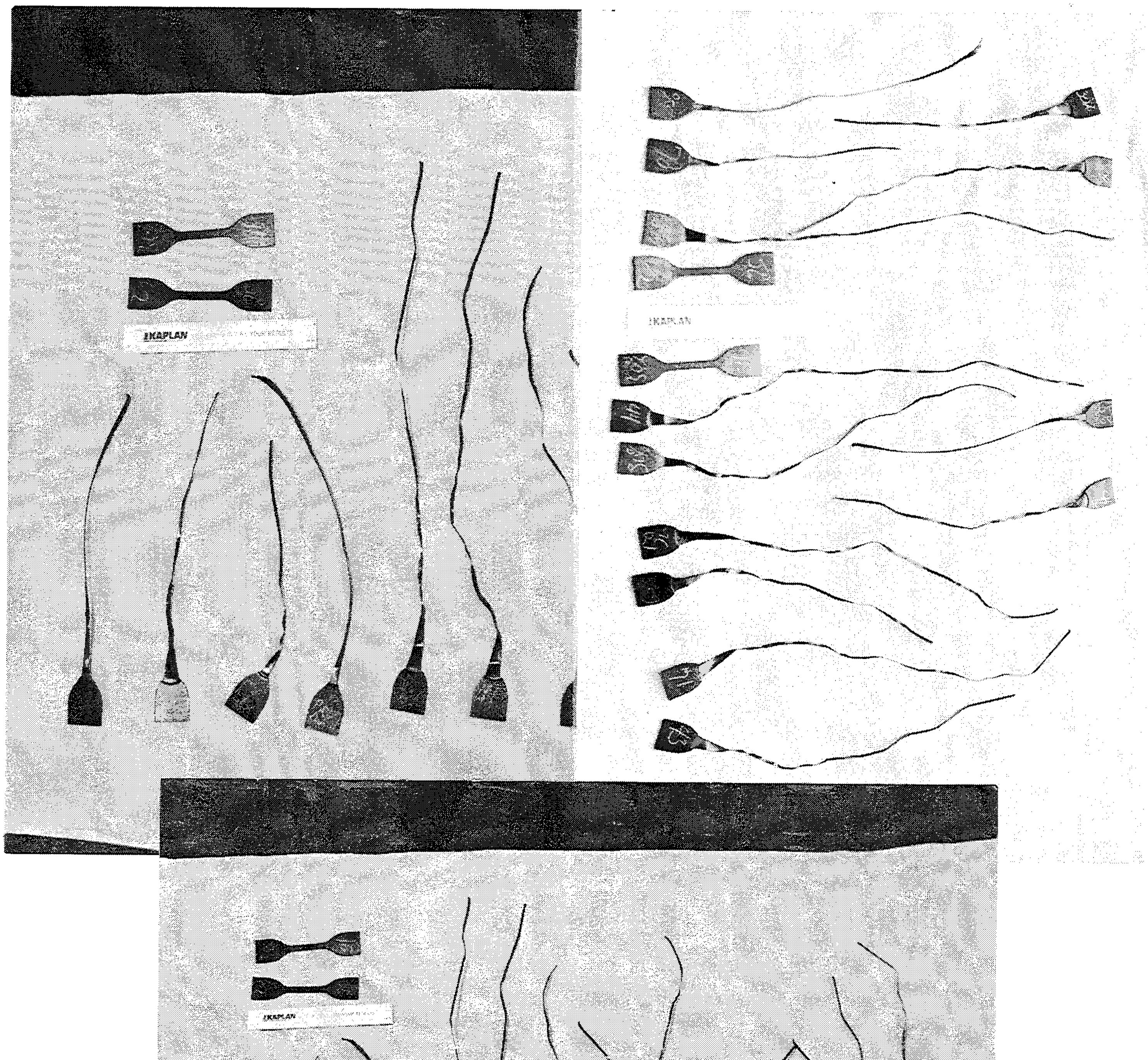
13	5	100	15.6	16.0	2.564103	5.448	5.464	2.165	2.164	-0.04619	0.088	0.087	1.037953	1.028696
14	5	100	15.2	15.6	2.631579	5.493	5.523	2.077	2.078	0.048146	0.083	0.081	0.946944	0.92962
Average:			14.6	14.85	1.684861	5.591833	5.614667	2.038333	2.038	-0.0159	0.083667	0.081333	0.95343	0.930626
Standard Deviation:			0.832666	0.919692	0.688409	0.218056	0.212896	0.066937	0.066671	0.097731	0.002211	0.002867	0.050605	0.055955
8	11	100	14.2	0	-100	5.851	0	1.980	0	-100	0.081	0	0.938383	0
12	11	100	14.1	0	-100	5.438	0	1.950	0	-100	0.086	0	0.911953	0
20	11	100	13.6	0	-100	5.401	0	1.989	0	-100	0.080	0	0.859407	0
21	11	100	13.6	0	-100	5.338	0	1.988	0	-100	0.082	0	0.870179	0
22	11	100	13.0	0	-100	5.389	0	1.970	0	-100	0.080	0	0.849306	0
23	11	100	14.7	0	-100	5.906	0	2.009	0	-100	0.069	0	0.818696	0
Average:			13.86667	0	-100	5.553833	0	1.981	0	-100	0.079667	0	0.874654	0
Standard Deviation:			0.540576	0	0	0.231969	0	0.018166	0	0	0.005185	0	0.039747	0

-0.89181	0.917161	0.949143	3.487014
-1.82941	0.979531	1.024042	4.544116
-2.42538	0.934753	0.97419	4.215867
0.881342	0.031091	0.033808	0.578188

-100	0.923436	ERR	ERR
-100	0.943508	ERR	ERR
-100	0.965692	ERR	ERR
-100	0.953738	ERR	ERR
-100	0.934066	ERR	ERR
-100	1.095705	ERR	ERR
-100	0.969358	ERR	ERR
0	0.058085	ERR	ERR

Appendix D

TENSILE PROPERTY DATA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MECHANICAL PROPERTIES LABORATORIES
BALLISTIC TEST DIVISION
NAVAL ORDNANCE STATION INDIAN HEAD, MD.

ASTM D TYPE IV

Test type: Tensile

Operator name: HUNTER

Sample Identification: HDP-1
Interface Type: 4500 Series
Machine Parameters of test:
Sample Rate (pts/sec): 50.00
Crosshead Speed (in/min): 2.000

Instron Corporation
Series IX Automated Materials Testing System v4.05a
Test Date: December 7,1990

Sample Type: ASTM

Humidity (%): 50
Temperature (deg. F): 73

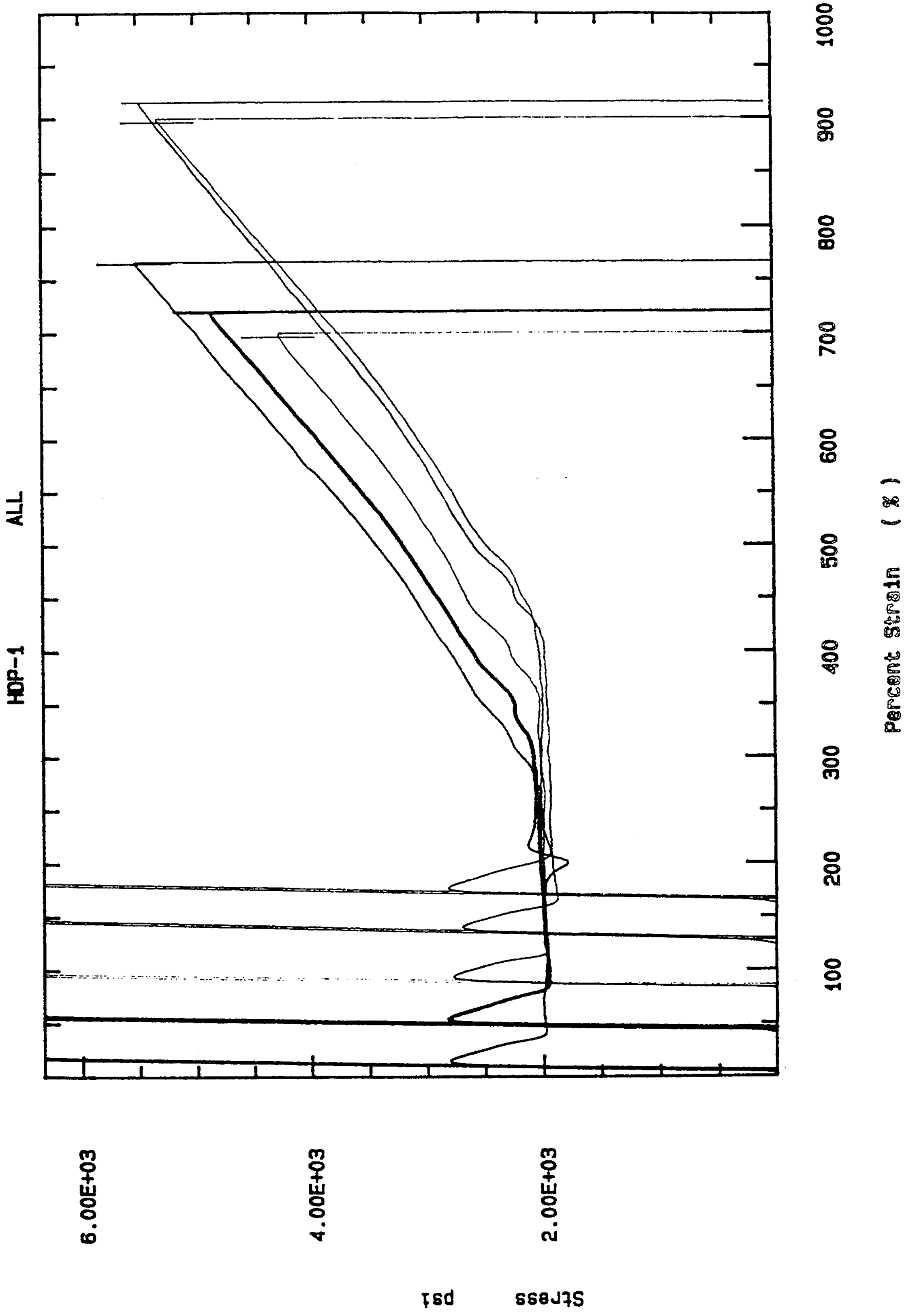
DATE MARCH 4, 1991
PROGRAM HIGH DENSITY POLYETHYLENE
ASTM SPECIFICATION D638/D882
COMMENTS SAMPLES 1 THRU 5
COMMENTS BASELINE

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5
Thickness (in)	.086000	.086000	.083000	.086000	.083000
Width (in)	.24400	.24400	.24500	.24400	.24400
Gauge length (in)	2.5000	2.5000	2.5000	2.5000	2.5000
Specimen G.L. (in)	3.0000	3.0000	3.0000	3.0000	3.0000

Out of 5 specimens, 0 excluded.
Sample comments: SHORE D HARDNESS 65

Specimen Number	Load/Width at Max.Load (lbs/in)	% Strain at Max.Load (%)	Strain at z-slp Yield (in/in)	Load/Width at z-slp Yield (lbs/in)	Modulus (psi)
1	475.4	762.2	.09794	240.6	51290.
2	418.9	675.5	.09204	242.1	54250.
3	354.2	614.8	.09293	229.4	55150.
4	471.3	787.0	.11570	230.6	35380.
5	442.6	734.1	.10660	233.0	42280.
Mean:	432.5	714.7	.10100	235.1	47670.
Standard Deviation:	49.4	69.6	.01002	5.8	8549.


HDP-1
ALL
Stress psi
6.00E+03
4.00E+03
2.00E+03
Percent Strain (%)
100
200
300
400
500
600
700
800
900
1000

MECHANICAL PROPERTIES LABORATORIES
BALLISTIC TEST DIVISION
NAVAL ORDNANCE STATION INDIAN HEAD, MD.

ASTM D TYPE IV

Test type: Tensile

Operator name: HUNTER

Sample Identification: HDP-2
Interface Type: 4500 Series
Machine Parameters of test:
Sample Rate (pts/sec): 50.00
Crosshead Speed (in/min): 2.000

Instron Corporation
Series IX Automated Materials Testing System v4.05a
Test Date: December 8,1990

Sample Type: ASTM

Humidity (%): 50
Temperature (deg. F): 73

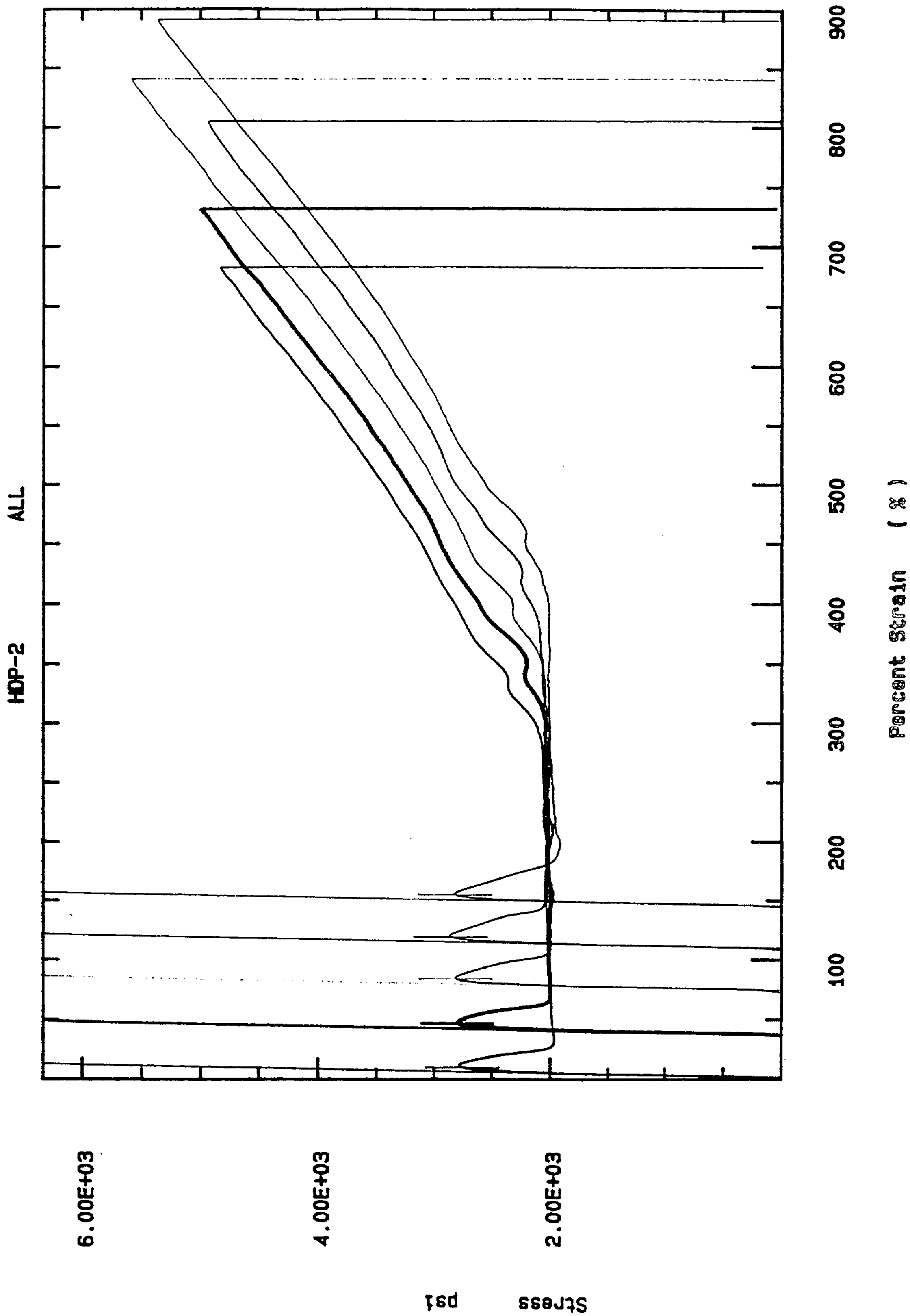
DATE MARCH 11, 1991
PROGRAM HIGH DENSITY POLYETHYLENE
ASTM SPECIFICATION D638/D882
COMMENTS 2 CYCLES 30%
COMMENTS SAMPLES 50,51,52,56,& 57

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5
Thickness (in)	.079000	.080000	.080000	.085000	.080000
Width (in)	.24500	.24400	.24500	.24300	.24400
Gauge length (in)	2.5000	2.5000	2.5000	2.5000	2.5000
Specimen G.L. (in)	3.0000	3.0000	3.0000	3.0000	3.0000

Out of 5 specimens, 0 excluded.

Specimen Number	Load/Width at Max.Load (lbs/in)	% Strain at Max.Load (%)	Strain at z-slp Yield (in/in)	Load/Width at z-slp Yield (lbs/in)	Modulus (psi)
1	381.7	680.7	.08251	217.5	54730.
2	401.1	694.7	.09477	224.1	54200.
3	447.3	765.5	.09421	224.7	53830.
4	419.8	694.8	.09438	242.5	52880.
5	429.5	745.3	.09358	225.4	54640.
Mean:	415.9	716.2	.09189	226.8	54060.
Standard Deviation:	25.4	36.9	.00526	9.3	750.



HDP-2
ALL
Stress psi
6.00E+03
4.00E+03
2.00E+03
Percent Strain (%)
100
200
300
400
500
600
700
800
900

MECHANICAL PROPERTIES LABORATORIES
BALLISTIC TEST DIVISION
NAVAL ORDNANCE STATION INDIAN HEAD, MD.

ASTM D TYPE IV

Test type: Tensile

Operator name: HUNTER

Sample Identification: HDP-3
Interface Type: 4500 Series
Machine Parameters of test:
Sample Rate (pts/sec): 50.00
Crosshead Speed (in/min): 2.000

Instron Corporation
Series IX Automated Materials Testing System v4.05a
Test Date: December 8,1990

Sample Type: ASTM

Humidity (%): 50
Temperature (deg. F): 73

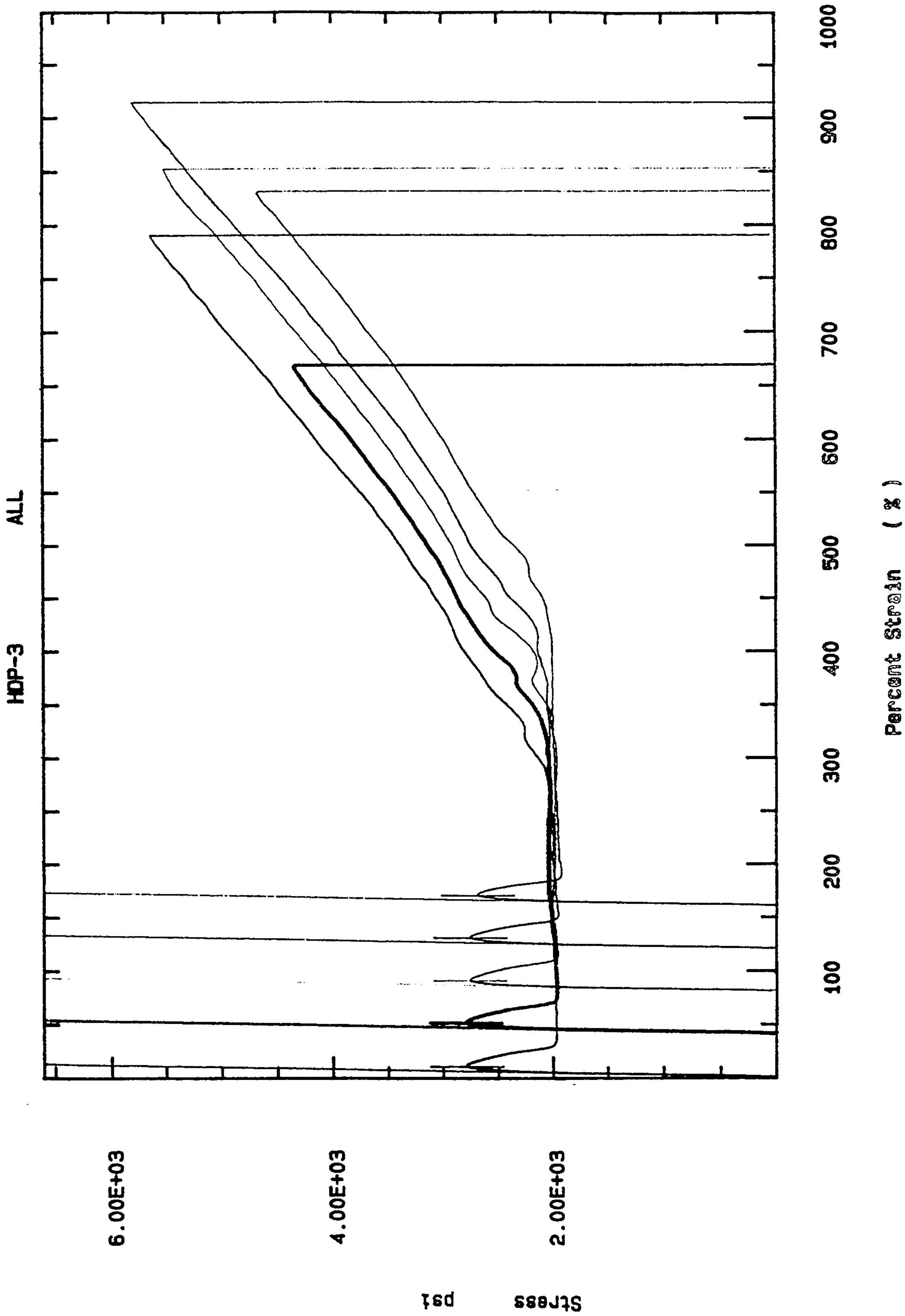
DATE MARCH 11, 1991
PROGRAM HIGH DENSITY POLYETHYLENE
ASTM SPECIFICATION D638/D882 SHORE D 65
COMMENTS 2 CYCLES 65%
COMMENTS SAMPLES 25,26,34,35, & 36

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5
Thickness (in)	.084000	.083000	.079000	.082000	.082000
Width (in)	.24500	.24400	.24400	.24400	.24400
Gauge length (in)	2.5000	2.5000	2.5000	2.5000	2.5000
Specimen G.L. (in)	3.0000	3.0000	3.0000	3.0000	3.0000

Out of 5 specimens, 0 excluded.

Specimen Number	Load/Width at Max.Load (lbs/in)	% Strain at Max.Load (%)	Strain at z-slp Yield (in/in)	Load/Width at z-slp Yield (lbs/in)	Modulus (psi)
1	473.5	788.5	.09244	233.9	55460.
2	361.6	626.5	.09703	232.1	52630.
3	435.2	770.6	.09463	217.5	54700.
4	476.2	792.8	.09552	225.8	53350.
5	383.2	668.9	.09246	220.4	53570.
Mean:	425.9	729.5	.09441	225.9	53940.
Standard Deviation:	52.1	76.6	.00199	7.1	1126.


HDP-3
ALL
Percent Strain (%)
100
200
300
400
500
600
700
800
900
1000
Stress psi
2.00E+03
4.00E+03
6.00E+03

MECHANICAL PROPERTIES LABORATORIES
BALLISTIC TEST DIVISION
NAVAL ORDNANCE STATION INDIAN HEAD, MD.

ASTM D TYPE IV

Test type: Tensile

Operator name: HUNTER

Sample Identification: HDP-4
Interface Type: 4500 Series
Machine Parameters of test:
Sample Rate (pts/sec): 50.00
Crosshead Speed (in/min): 2.000

Instron Corporation
Series IX Automated Materials Testing System v4.05a
Test Date: December 8,1990

Sample Type: ASTM

Humidity (%): 50
Temperature (deg. F): 73

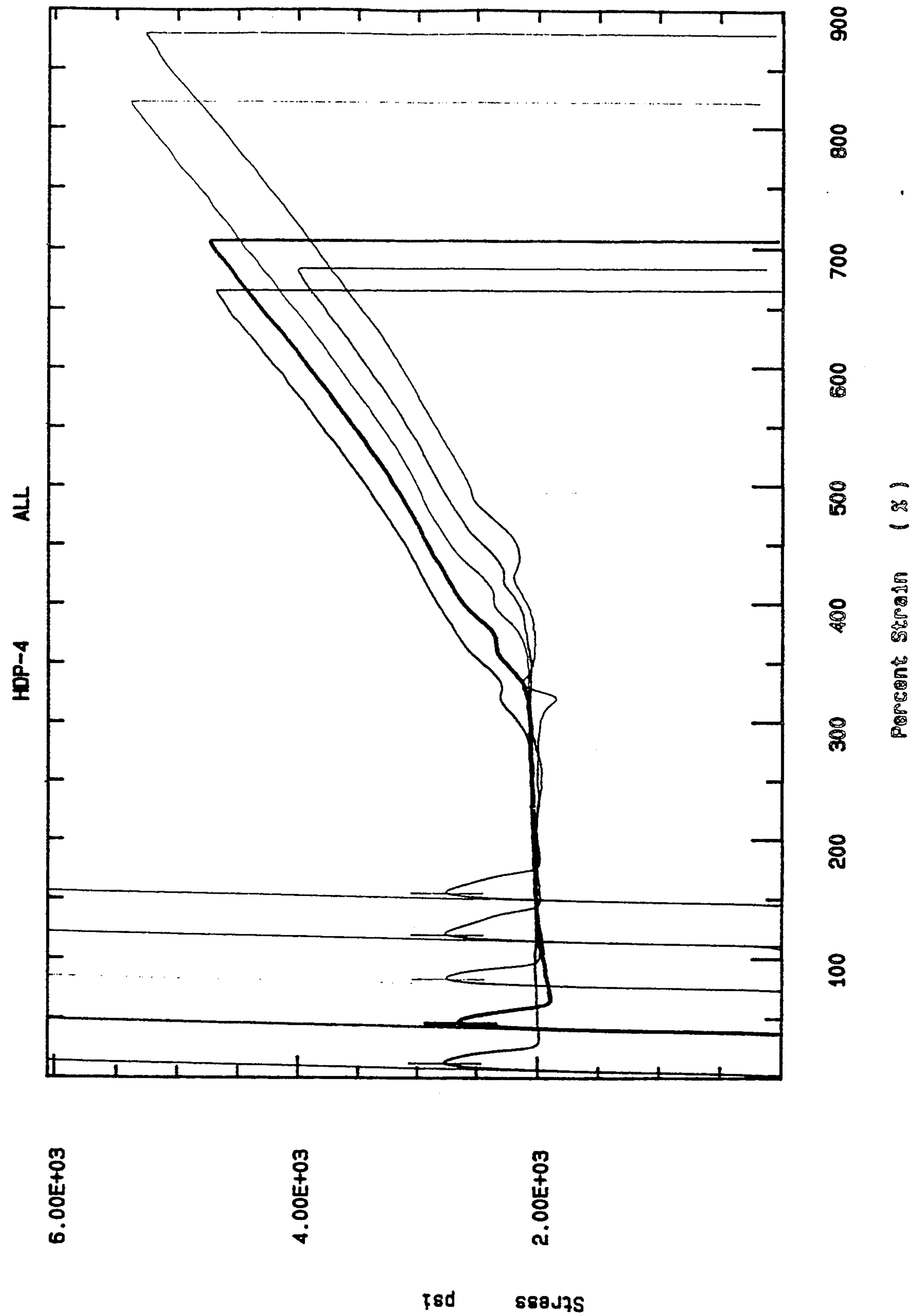
DATE MARCH 11, 1991
PROGRAM HIGH DENSITY POLYETHYLENE
ASTM SPECIFICATION D638/D882 SHORE D 65
COMMENTS 2 CYCLES 5%
COMMENTS SAMPLES 25,28,39,75, & 75

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5
Thickness (in)	.083000	.083000	.082000	.081000	.083000
Width (in)	.24400	.24400	.24400	.24400	.24400
Gauge length (in)	2.5000	2.5000	2.5000	2.5000	2.5000
Specimen G.L. (in)	3.0000	3.0000	3.0000	3.0000	3.0000

Out of 5 specimens, 0 excluded.

Specimen Number	Load/Width at Max.Load (lbs/in)	% Strain at Max.Load (%)	Strain at z-slp Yield (in/in)	Load/Width at z-slp Yield (lbs/in)	Modulus (psi)
1	389.2	661.5	.09666	229.3	51490.
2	394.0	667.9	.08781	218.7	50760.
3	442.2	747.1	.09103	224.4	52300.
4	324.6	570.4	.08908	222.3	52110.
5	437.7	733.7	.09268	228.4	53660.
Mean:	397.5	676.1	.09145	224.6	52060.
Standard Deviation:	47.5	70.4	.00345	4.4	1077.


HDP-4
ALL
Percent Strain (%)
100
200
300
400
500
600
700
800
900
Stress psi
2.00E+03
4.00E+03
6.00E+03

MECHANICAL PROPERTIES LABORATORIES
BALLISTIC TEST DIVISION
NAVAL ORDNANCE STATION INDIAN HEAD, MD.

ASTM D TYPE IV

Test type: Tensile

Operator name: HUNTER

Sample Identification: HDP-5
Interface Type: 4500 Series
Machine Parameters of test:
Sample Rate (pts/sec): 50.00
Crosshead Speed (in/min): 2.000

Instron Corporation
Series IX Automated Materials Testing System v4.05a
Test Date: December 8,1990

Sample Type: ASTM

Humidity (%): 50
Temperature (deg. F): 73

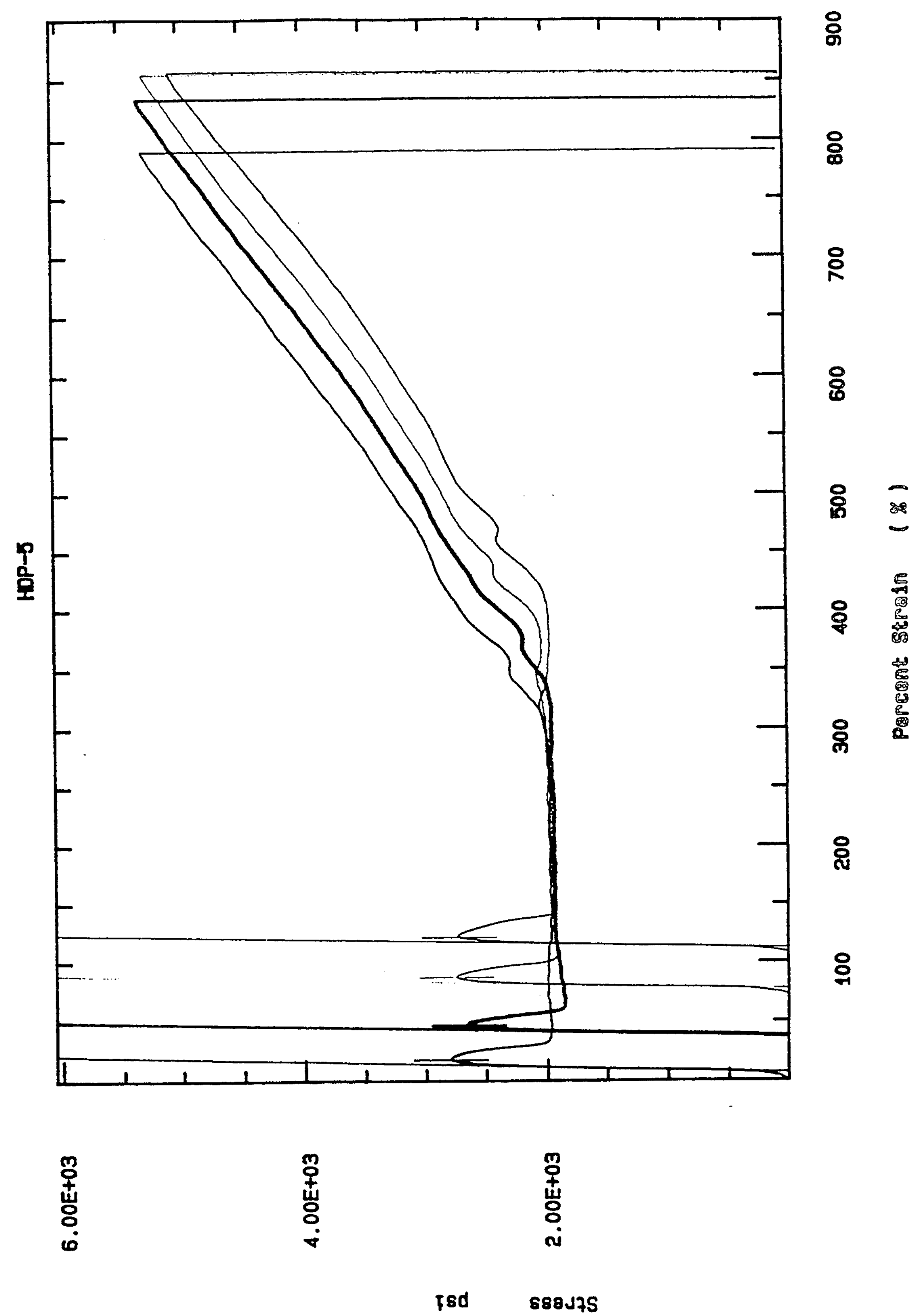
DATE MARCH 8, 1991
PROGRAM HIGH DENSITY POLYETHYLENE
ASTM SPECIFICATION D638/D882
COMMENTS 2 CYCLES 100%
COMMENTS

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5
Thickness (in)	.082000	.081000	.082000	.089000	.083000
Width (in)	.24400	.24500	.24400	.24200	.24400
Gauge length (in)	2.5000	2.5000	2.5000	2.5000	2.5000
Specimen G.L. (in)	3.0000	3.0000	3.0000	3.0000	3.0000

Out of 5 specimens, 1 excluded.

Specimen Number	Load/Width at Max.Load (lbs/in)	% Strain at Max.Load (%)	Strain at z-slp Yield (in/in)	Load/Width at z-slp Yield (lbs/in)	Modulus (psi)
1	435.7	784.2	.11190	228.5	39490.
2	433.9	796.8	.08965	214.1	48320.
3	434.8	776.9	.10110	224.4	49030.
4	451.7	743.6	.09404	241.4	49270.
Excluded	449.2	792.9	.09886	230.6	50130.
Mean:	439.0	775.4	.09917	227.1	46530.
Standard Deviation:	8.5	22.7	.00970	11.3	4711.


HDP-5
Percent Strain (%)
100
200
300
400
500
600
700
800
900
Stress psi
2.00E+03
4.00E+03
6.00E+03

MECHANICAL PROPERTIES LABORATORIES
BALLISTIC TEST DIVISION
NAVAL ORDNANCE STATION INDIAN HEAD, MD.

ASTM D TYPE IV

Test type: Tensile

Operator name: HUNTER

Sample Identification: HDP-5A
Interface Type: 4500 Series
Machine Parameters of test:
Sample Rate (pts/sec): 50.00
Crosshead Speed (in/min): 2.000

Instron Corporation
Series IX Automated Materials Testing System v4.05a
Test Date: December 8,1990

Sample Type: ASTM

Humidity (%): 50
Temperature (deg. F): 73

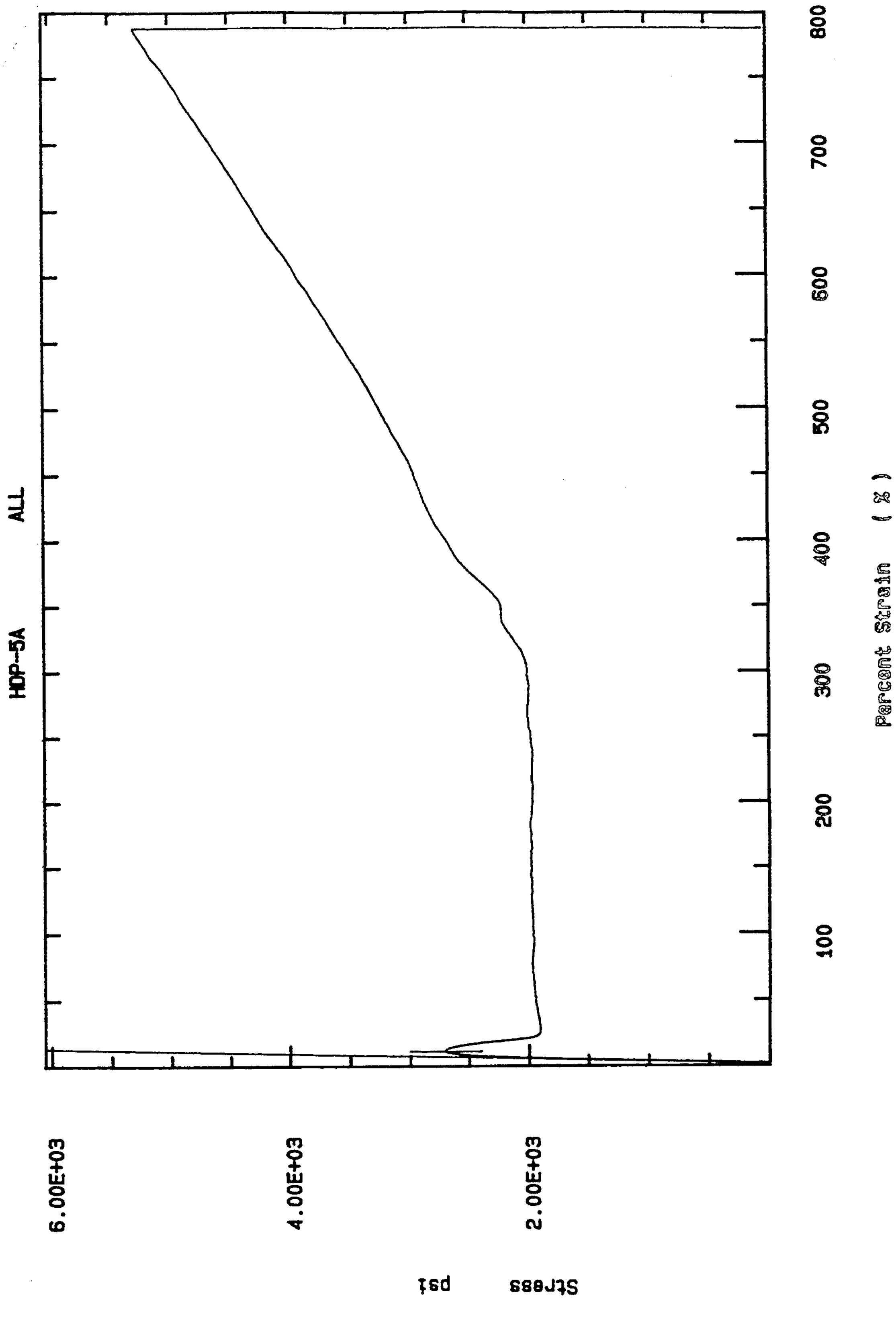
DATE MARCH 8, 1991
PROGRAM HIGH DENSITY POLYETHYLENE
ASTM SPECIFICATION D638/D882
COMMENTS 2 CYCLES 100%
COMMENTS SAMPLE #24

Dimensions:

	Spec. 1
Thickness (in)	.080000
Width (in)	.24400
Gauge length (in)	2.5000
Specimen G.L. (in)	3.0000

Out of 1 specimens, 0 excluded.

Specimen Number	Load/Width at Max.Load (lbs/in)	% Strain at Max.Load (%)	Strain at z-slp Yield (in/in)	Load/Width at z-slp Yield (lbs/in)	Modulus (psi)
1	423.8	785.6	.09352	215.5	51430.
Mean:	423.8	785.6	.09352	215.5	51430.
Standard Deviation:	----------	----------	----------	----------	----------


HDP-5A
ALL
Percent Strain (%)
100
200
300
400
500
600
700
800
Stress psi
6.00E+03
4.00E+03
2.00E+03

MECHANICAL PROPERTIES LABORATORIES
BALLISTIC TEST DIVISION
NAVAL ORDNANCE STATION INDIAN HEAD, MD.

ASTM D TYPE IV

Test type: Tensile

Operator name: HUNTER

Sample Identification: HDP-6
Interface Type: 4500 Series
Machine Parameters of test:
Sample Rate (pts/sec): 50.00
Crosshead Speed (in/min): 2.000

Instron Corporation
Series II Automated Materials Testing System v4.05a
Test Date: December 8,1990

Sample Type: ASTM

Humidity (%): 50
Temperature (deg. F): 73

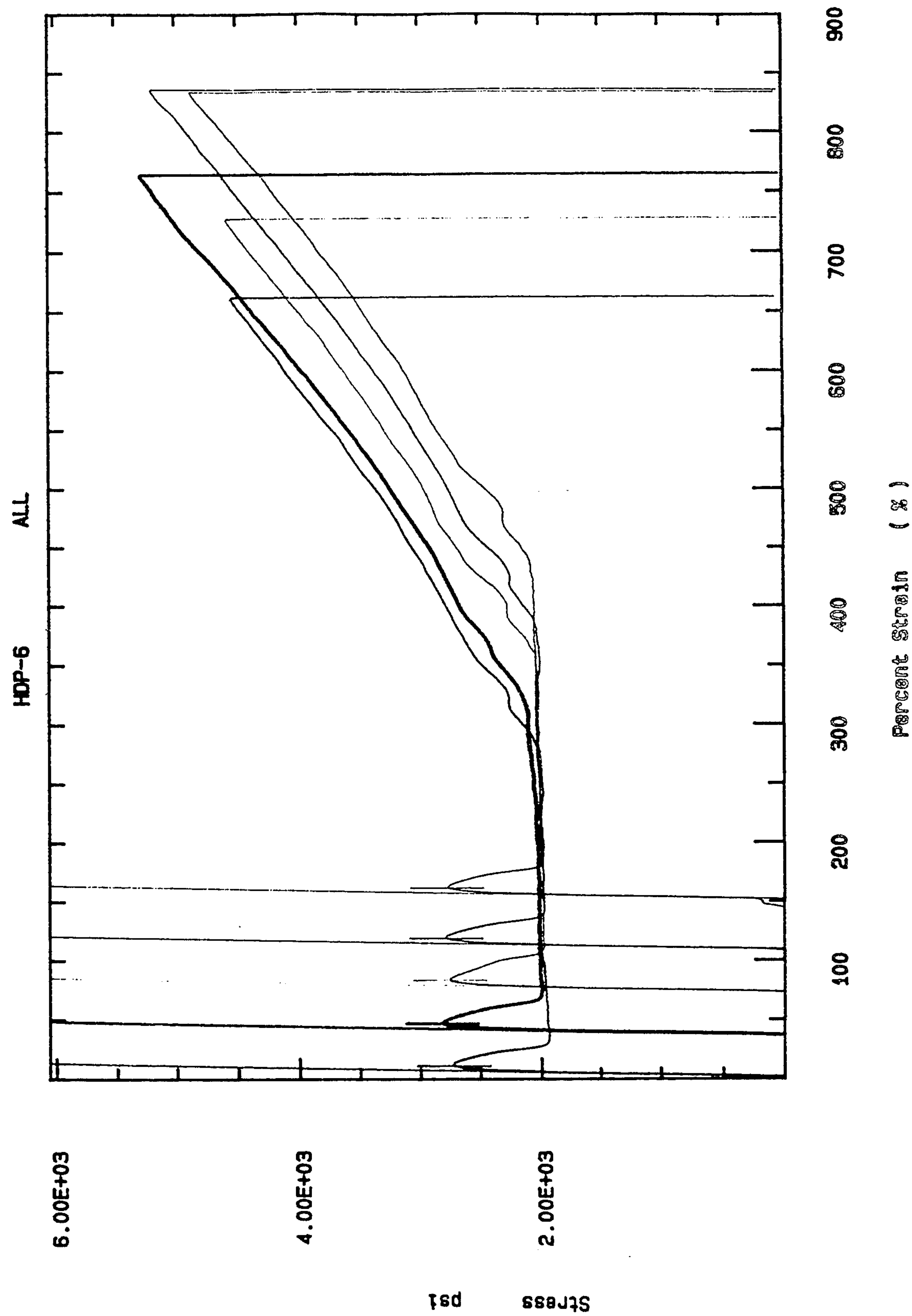
DATE MARCH 11, 1991
PROGRAM HIGH DENSITY POLYETHYLENE
ASTM SPECIFICATION D638/D882 SHORE D 60
COMMENTS 5 CYCLES 5%
COMMENTS SAMPLES 64,65,67,70, & 73

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5
Thickness (in)	.080000	.080000	.088000	.083000	.083000
Width (in)	.24600	.24500	.24700	.24500	.24500
Gauge length (in)	2.5000	2.5000	2.5000	2.5000	2.5000
Specimen G.L. (in)	3.0000	3.0000	3.0000	3.0000	3.0000

Out of 5 specimens, 0 excluded.

Specimen Number	Load/Width at Max.Load (lbs/in)	% Strain at Max.Load (%)	Strain at z-slp Yield (in/in)	Load/Width at z-slp Yield (lbs/in)	Modulus (psi)
1	363.8	658.3	.09265	217.3	51510.
2	424.1	726.6	.09769	225.1	52580.
3	403.8	652.6	.09883	241.8	52260.
4	431.8	725.3	.09486	230.6	53170.
5	405.3	681.9	.09949	229.4	49850.
Mean:	405.8	688.9	.09670	228.8	51870.
Standard Deviation:	26.4	35.5	.00288	8.9	1278.


HDP-6
ALL
Stress psi
6.00E+03
4.00E+03
2.00E+03
Percent Strain (%)
100
200
300
400
500
600
700
800
900

MECHANICAL PROPERTIES LABORATORIES
BALLISTIC TEST DIVISION
NAVAL ORDNANCE STATION INDIAN HEAD, MD.

ASTM D TYPE IV

Test type: Tensile

Operator name: HUNTER

Sample Identification: HDP-7
Interface Type: 4500 Series
Machine Parameters of test:
Sample Rate (pts/sec): 50.00
Crosshead Speed (in/min): 2.000

Instron Corporation
Series IX Automated Materials Testing System v4.05a
Test Date: December 8,1990

Sample Type: ASTM

Humidity (%): 50
Temperature (deg. F): 73

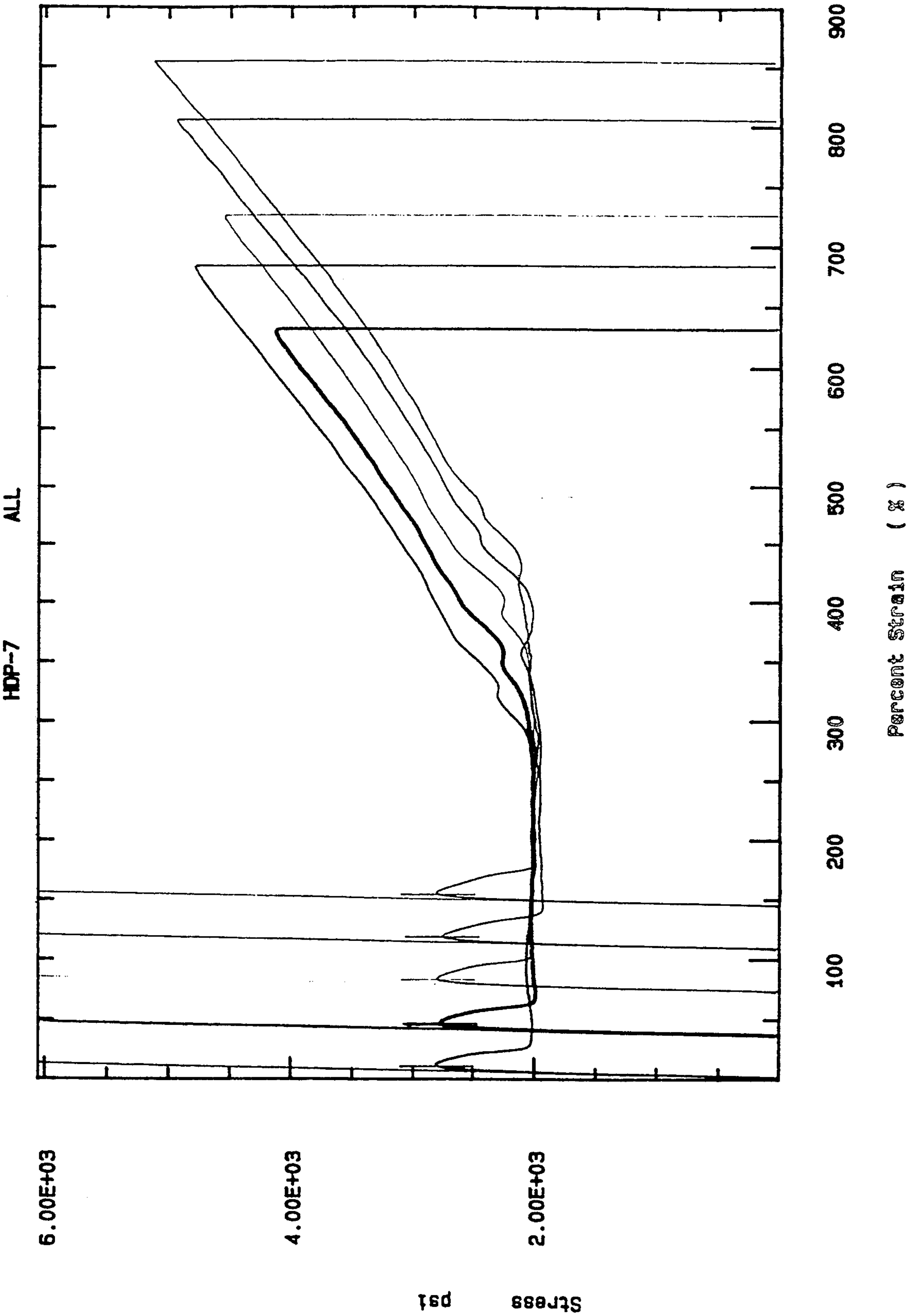
DATE	MARCH 12, 1991
PROGRAM	HIGH DENSITY POLYETHYLENE
ASTM SPECIFICATION	D638/D882
COMMENTS	5 CYCLES 30% SHORE D 58
COMMENTS	SAMPLES 47,48,49,55, & 59

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5
Thickness (in)	.083000	.078000	.087000	.080000	.081000
Width (in)	.24500	.24600	.24500	.24400	.24400
Gauge length (in)	2.5000	2.5000	2.5000	2.5000	2.5000
Specimen G.L. (in)	3.0000	3.0000	3.0000	3.0000	3.0000

Out of 5 specimens, 0 excluded.

Specimen Number	Load/Width at Max.Load (lbs/in)	% Strain at Max.Load (%)	Strain at z-slp Yield (in/in)	Load/Width at z-slp Yield (lbs/in)	Modulus (psi)
1	397.8	680.4	.09060	231.8	52270.
2	322.7	592.8	.09289	216.1	53590.
3	396.0	650.8	.09266	242.3	52410.
4	395.4	694.9	.09314	219.9	54330.
5	415.6	708.7	.08652	225.8	56480.
Mean:	385.5	665.5	.09116	227.2	53820.
Standard Deviation:	36.1	46.0	.00278	10.4	1717.


HDP-7
ALL
Percent Strain (%)
Stress psi
6.00E+03
4.00E+03
2.00E+03
100
200
300
400
500
600
700
800
900

MECHANICAL PROPERTIES LABORATORIES
BALLISTIC TEST DIVISION
NAVAL ORDNANCE STATION INDIAN HEAD, MD.

ASTM D TYPE IV

Test type: Tensile

Operator name: HUNTER

Sample Identification: HDP-8
Interface Type: 4500 Series
Machine Parameters of test:
Sample Rate (pts/sec): 50.00
Crosshead Speed (in/min): 2.000

Instron Corporation
Series IX Automated Materials Testing System v4.05a
Test Date: December 8,1990

Sample Type: ASTM

Humidity (%): 50
Temperature (deg. F): 73

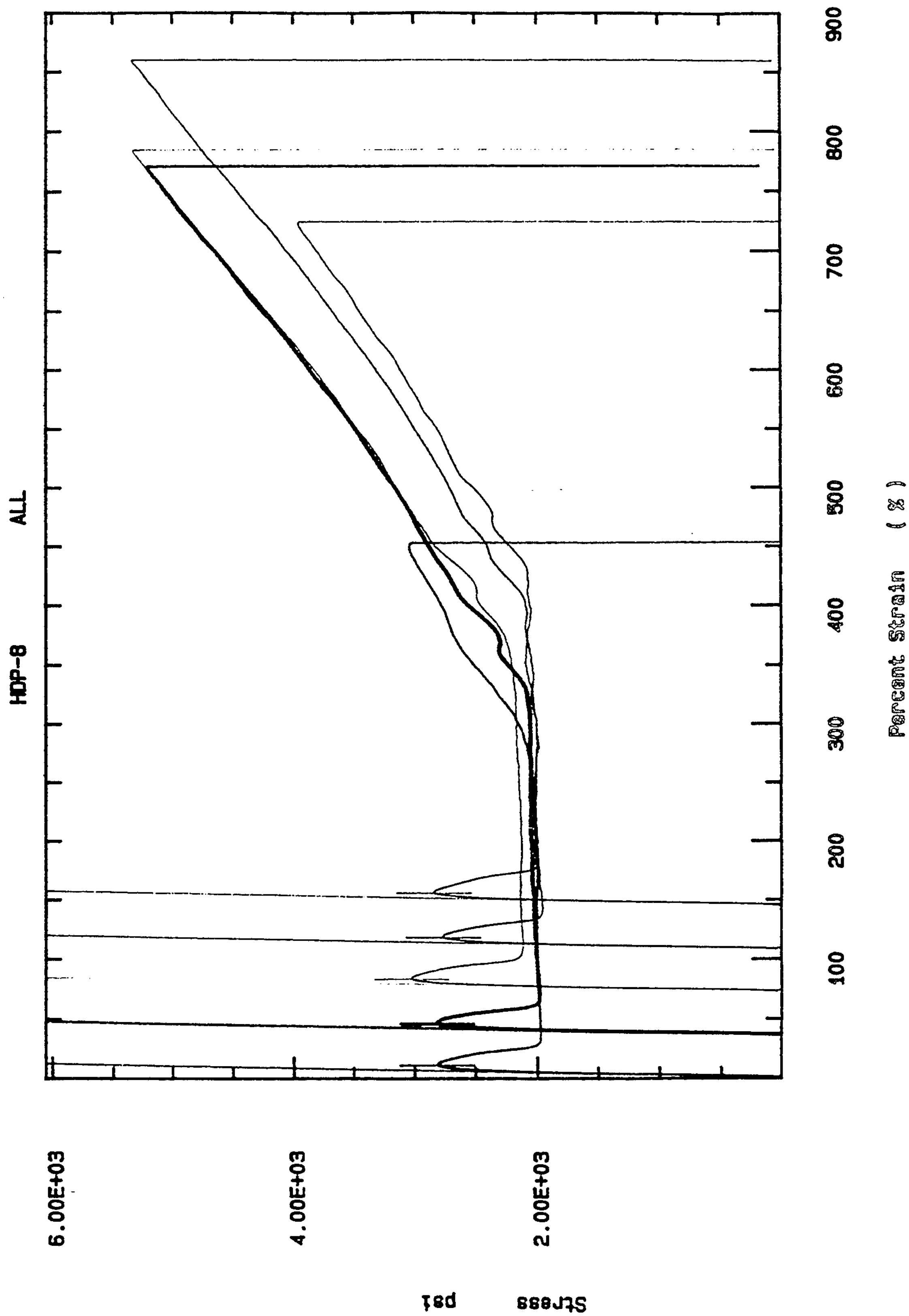
DATE MARCH 12, 1991
PROGRAM HIGH DENSITY POLYETHYLENE
ASTM SPECIFICATION D638/D882
COMMENTS 5 CYCLES @5% SHORE D 58
COMMENTS SAMPLES 30,37,38,39, & 40

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5
Thickness (in)	.087000	.083000	.080000	.080000	.083000
Width (in)	.24500	.24500	.24400	.24400	.24500
Gauge length (in)	2.5000	2.5000	2.5000	2.5000	2.5000
Specimen G.L. (in)	3.0000	3.0000	3.0000	3.0000	3.0000

Out of 5 specimens, 0 excluded.

Specimen Number	Load/Width at Max.Load (lbs/in)	% Strain at Max.Load (%)	Strain at z-slp Yield (in/in)	Load/Width at z-slp Yield (lbs/in)	Modulus (psi)
1	264.9	447.5	.09626	244.5	53870.
2	433.5	732.9	.09006	233.4	54990.
3	426.6	709.6	.09561	241.6	56560.
4	427.9	750.0	.09174	220.8	54720.
5	329.2	576.5	.09595	235.6	52670.
Mean:	376.4	643.3	.09392	235.2	54560.
Standard Deviation:	76.0	129.0	.00284	9.2	1436.


HDP-8
ALL
Stress psi
6.00E+03
4.00E+03
2.00E+03
100
200
300
400
500
600
700
800
900
Percent Strain (%)

MECHANICAL PROPERTIES LABORATORIES
BALLISTIC TEST DIVISION
NAVAL ORDNANCE STATION INDIAN HEAD, MD.

ASTM D TYPE IV

Test type: Tensile

Operator name: HUNTER

Sample Identification: HDP-9
Interface Type: 4500 Series
Machine Parameters of test:
Sample Rate (pts/sec): 50.00
Crosshead Speed (in/min): 2.000

Instron Corporation
Series IX Automated Materials Testing System v4.05a
Test Date: December 8,1990

Sample Type: ASTM

Humidity (%): 50
Temperature (deg. F): 73

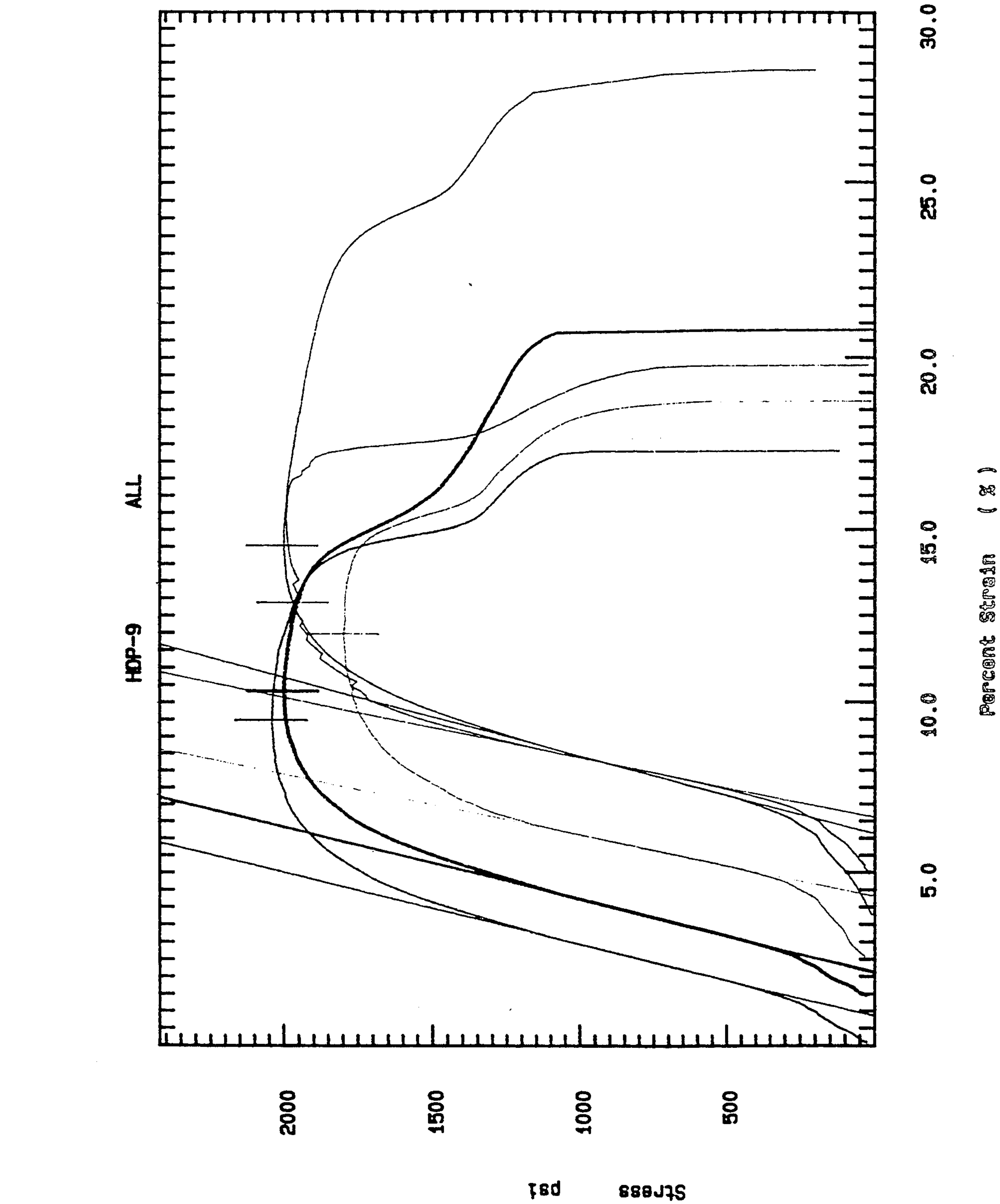
DATE MARCH 11, 1991
PROGRAM HIGH DENSITY POLYETHYLENE
ASTM SPECIFICATION D638/D882
COMMENTS 5 CYCLES 100%
COMMENTS SAMPLES 7,9,10,11, & 13

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5
Thickness (in)	.078000	.080000	.077000	.078000	.084000
Width (in)	.24400	.24500	.24300	.24400	.24400
Gauge length (in)	2.5000	2.5000	2.5000	2.5000	2.5000
Specimen G.L. (in)	3.0000	3.0000	3.0000	3.0000	3.0000

Out of 5 specimens, 0 excluded.

Specimen Number	Load/Width at Max.Load (lbs/in)	% Strain at Max.Load (%)	Strain at z-slp Yield (in/in)	Load/Width at z-slp Yield (lbs/in)	Modulus (psi)
1	159.3	8.470	.08606	159.2	48200.
2	160.4	8.362	.08181	160.3	47610.
3	138.5	7.629	.07637	138.5	56120.
4	156.1	8.392	.08394	156.1	43700.
5	167.4	8.798	.06245	165.2	56810.
Mean:	156.3	8.330	.07813	155.9	50490.
Standard Deviation:	10.8	.429	.00948	10.3	5728.


HDP-9
ALL
Percent Strain (%)
5.0
10.0
15.0
20.0
25.0
30.0
Stress psi
2000
1500
1000
500

MECHANICAL PROPERTIES LABORATORIES
BALLISTIC TEST DIVISION
NAVAL ORDNANCE STATION INDIAN HEAD, MD.

ASTM D TYPE IV

Test type: Tensile

Operator name: HUNTER

Sample Identification: HDP-10
Interface Type: 4500 Series
Machine Parameters of test:
Sample Rate (pts/sec): 50.00
Crosshead Speed (in/min): 2.000

Instron Corporation
Series IX Automated Materials Testing System v4.05a
Test Date: December 9,1990

Sample Type: ASTM

Humidity (%): 50
Temperature (deg. F): 73

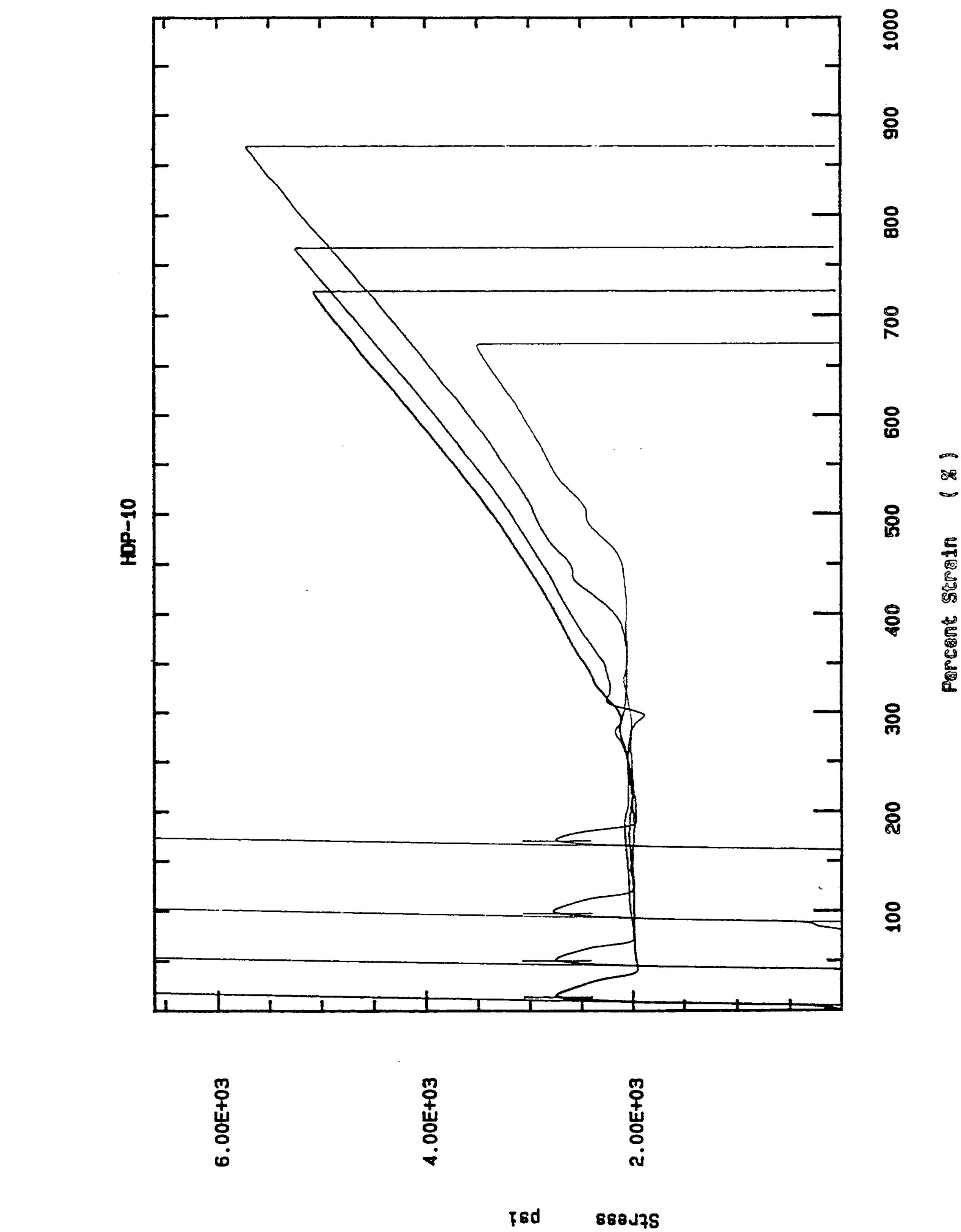
DATE MARCH 19, 1991
PROGRAM HIGH DENSITY POLYETHYLENE
ASTM SPECIFICATION D638/D882 SHORE D 62
COMMENTS SAMPLES 61,62,63,71, & 73
COMMENTS 5% 15 CYCLES

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7
Thickness (in)	.080000	.082000	.082000	.082000	.082000	.082000	.081000
Width (in)	.24500	.24400	.24400	.24400	.24400	.24400	.24500
Gauge length (in)	2.5000	2.5000	2.5000	2.5000	2.5000	2.5000	2.5000
Specimen G.L. (in)	3.0000	3.0000	3.0000	3.0000	3.0000	3.0000	3.0000

Out of 7 specimens, 2 excluded.

Specimen Number	Load/Width at Max.Load (lbs/in)	% Strain at Max.Load (%)	Strain at z-slp Yield (in/in)	Load/Width at z-slp Yield (lbs/in)	Modulus (psi)
1	406.50	717.900	.089560	217.700	49070.
Excluded	67.87	9.292	.052900	14.020	4740.
Excluded	10.18	5.281	.002583	2.404	11710.
4	430.30	724.600	.090860	224.500	54040.
5	469.70	779.700	.088900	223.200	46460.
6	462.70	796.000	.090430	216.500	42860.
7	284.30	508.500	.091520	221.800	52300.
Mean:	410.70	705.300	.090260	220.700	48950.
Standard Deviation:	75.09	115.100	.001038	3.472	4481.


HDP-10
Percent Strain (%)
Stress psi
2.00E+03
4.00E+03
6.00E+03
100
200
300
400
500
600
700
800
900
1000

MECHANICAL PROPERTIES LABORATORIES
BALLISTIC TEST DIVISION
NAVAL ORDNANCE STATION INDIAN HEAD, MD.

ASTM D TYPE IV

Test type: Tensile

Operator name: HUNTER

Sample Identification: HDP-11
Interface Type: 4500 Series
Machine Parameters of test:
Sample Rate (pts/sec): 50.00
Crosshead Speed (in/min): 2.000

Instron Corporation
Series IX Automated Materials Testing System v4.05a
Test Date: December 9,1990

Sample Type: ASTM

Humidity (%): 50
Temperature (deg. F): 73

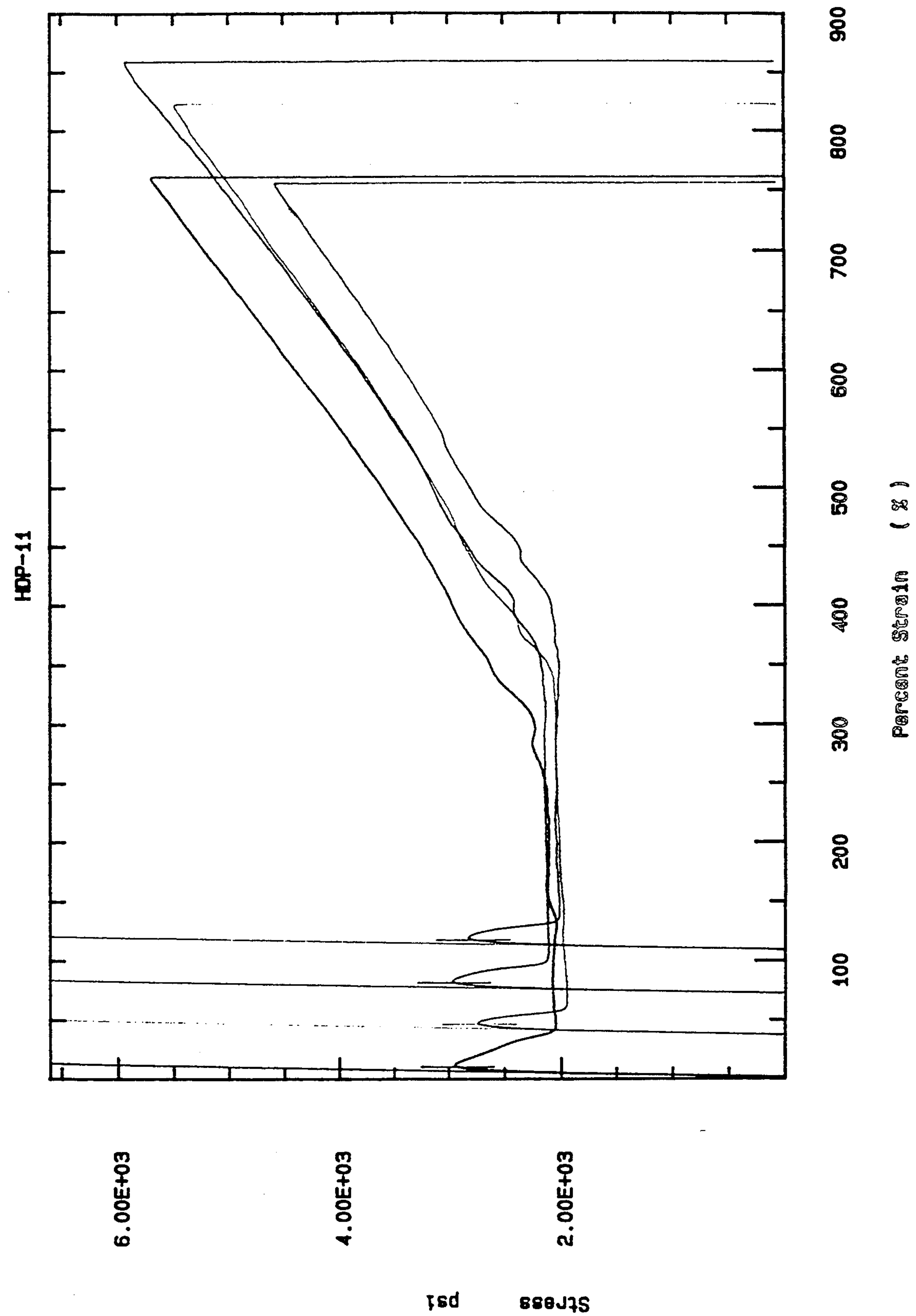
DATE MARCH 19, 1991
PROGRAM HIGH DENSITY POLYETHYLENE
ASTM SPECIFICATION D638/D882 SHORE D 64
COMMENTS SAMPLES 43,44,45,46, & 53
COMMENTS 30% 15 CYCLES

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6
Thickness (in)	.082000	.080000	.080000	.081000	.081000	.082000
Width (in)	.24400	.24400	.24400	.24400	.24400	.24400
Gauge length (in)	2.5000	2.5000	2.5000	2.5000	2.5000	2.5000
Specimen G.L. (in)	3.0000	3.0000	3.0000	3.0000	3.0000	3.0000

Out of 6 specimens, 1 excluded.

Specimen Number	Load/Width at Max.Load (lbs/in)	% Strain at Max.Load (%)	Strain at z-slp Yield (in/in)	Load/Width at z-slp Yield (lbs/in)	Modulus (psi)
1	468.0	758.3	.08799	239.6	55920.
Excluded	468.0	759.6	----------	----------	1858000.
3	439.8	782.9	.09020	218.0	52010.
4	481.1	785.9	.09034	239.2	58420.
5	371.9	646.2	.08141	225.4	57480.
6	376.1	660.7	.08761	223.6	52890.
Mean:	427.4	726.8	.08751	229.2	55340.
Standard Deviation:	51.0	68.0	.00363	9.7	2806.


HDP-11
Percent Strain (%)
100
200
300
400
500
600
700
800
900
Stress psi
2.00E+03
4.00E+03
6.00E+03

MECHANICAL PROPERTIES LABORATORIES
BALLISTIC TEST DIVISION
NAVAL ORDNANCE STATION INDIAN HEAD, MD.

ASTM D TYPE IV

Test type: Tensile

Operator name: HUNTER

Sample Identification: HDP-12
Interface Type: 4500 Series
Machine Parameters of test:
Sample Rate (pts/sec): 50.00
Crosshead Speed (in/min): 2.000

Instron Corporation
Series IX Automated Materials Testing System v4.05a
Test Date: December 9,1990

Sample Type: ASTM

Humidity (%): 50
Temperature (deg. F): 73

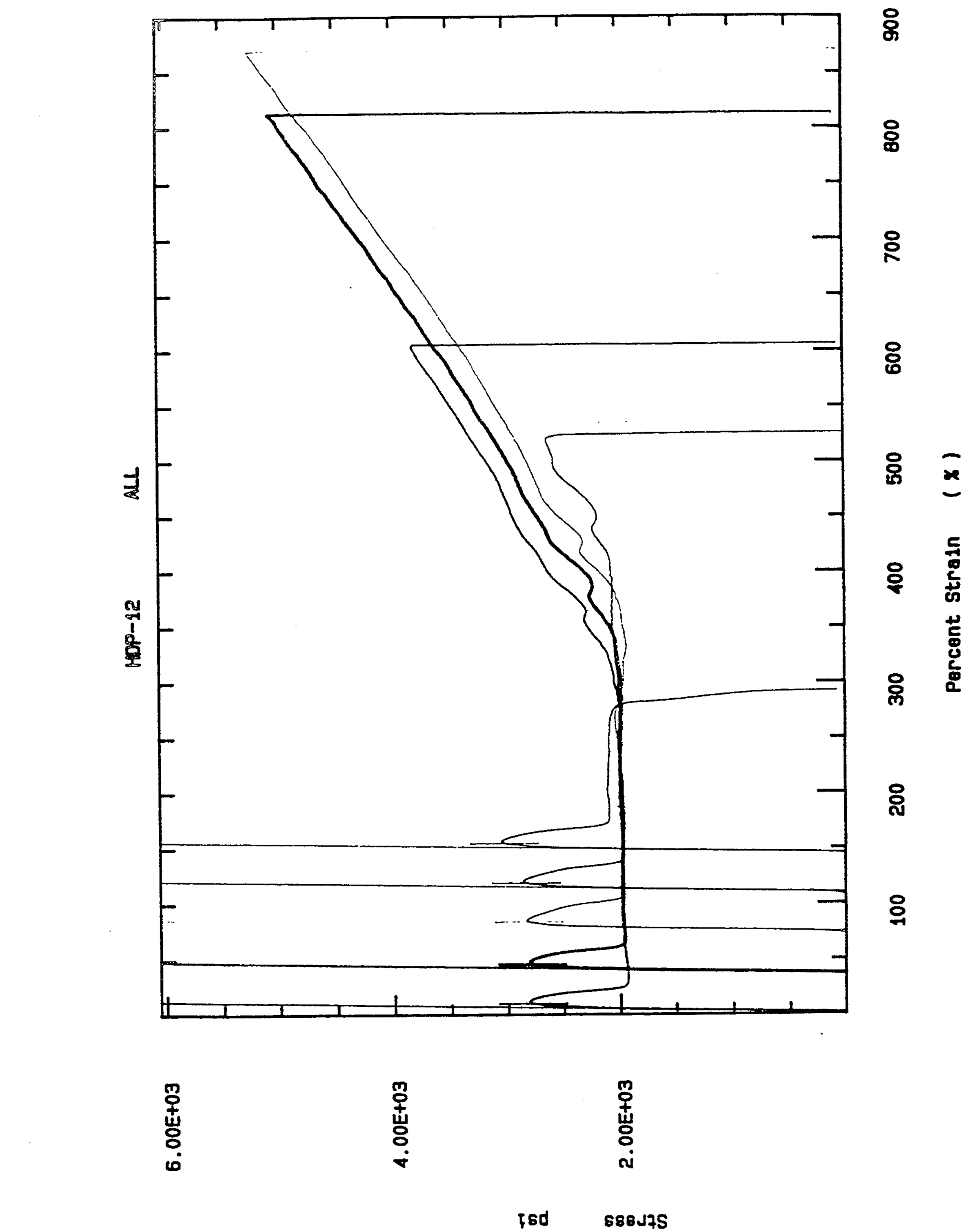
DATE MARCH 19, 1991
PROGRAM HIGH DENSITY POLYETHYLENE
ASTM SPECIFICATION D638/D882 SHORE D 64
COMMENTS SAMPLES 27,28,29,31, & 32
COMMENTS 65% 15 CYCLES

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6
Thickness (in)	.081000	.081000	.081000	.080000	.081000	.081000
Width (in)	.24400	.24400	.24400	.24400	.24400	.24400
Gauge length (in)	2.5000	2.5000	2.5000	2.5000	2.5000	2.5000
Specimen G.L. (in)	3.0000	3.0000	3.0000	3.0000	3.0000	3.0000

Out of 6 specimens, 0 excluded.

Specimen Number	Load/Width at Max.Load (lbs/in)	% Strain at Max.Load (%)	Strain at z-slp Yield (in/in)	Load/Width at z-slp Yield (lbs/in)	Modulus (psi)
1	310.1	602.30	.08433	225.0	54930.
2	411.9	776.00	.08636	225.8	53480.
3	425.8	795.00	.09031	227.7	52340.
4	229.0	10.42	.08737	226.5	53600.
5	247.8	10.41	.08909	245.4	56720.
6	230.7	444.50	.09440	222.2	48090.
Mean:	309.2	439.80	.08864	228.8	53190.
Standard Deviation:	90.0	356.20	.00351	8.4	2913.


HDP-12
ALL
6.00E+03
4.00E+03
2.00E+03
Stress psi
100
200
300
400
500
600
700
800
900
Percent Strain (%)

HDPE SAMPLE TESTING IN ACID
CALCULATE LOAD/AREA FROM LOAD/WIDTH (AS REPORTED)
HDPE Testing; quattro; hdpe-1

Baseline	Thick	Ld/Wid.M lb/in	Ld/A Max lb/in2	Ld/Wid.Y lb/in	Ld/A Yld lb/in2
	0.086	475.4	5527.91	240.6	2797.67
	0.086	418.9	4870.93	242.1	2815.12
	0.083	354.2	4267.47	229.4	2763.86
	0.086	471.3	5480.23	230.6	2681.40
	0.083	442.6	5332.53	233	2807.23
	Mean	432.48	5095.81	235.14	2773.05
	Std. Dev.	44.19	474.81	5.22	49.05

2 x 5%	Thick	Ld/Wid.M lb/in	Ld/A Max lb/in2	Ld/Wid.Y lb/in	Ld/A Yld lb/in2
	0.083	389.2	4689.16	229.3	2762.65
	0.083	394	4746.99	218.7	2634.94
	0.082	442.2	5392.68	224.4	2736.59
	0.081	324.6	4007.41	222.3	2744.44
	0.083	437.7	5273.49	228.4	2751.81
	Mean	397.54	4821.95	224.62	2726.09
	Std. Dev.	42.45	493.23	3.92	46.38

5 x 5%	Thick	Ld/Wid.M lb/in	Ld/A Max lb/in2	Ld/Wid.Y lb/in	Ld/A Yld lb/in2
	0.08	363.8	4547.50	217.3	2716.25
	0.08	424.1	5301.25	225.1	2813.75
	0.088	403.8	4588.64	241.8	2747.73
	0.083	431.8	5202.41	230.6	2778.31
	0.083	405.3	4883.13	229.4	2763.86
	Mean	405.76	4904.59	228.84	2763.98
	Std. Dev.	23.58	307.84	7.98	32.33

15 x 5%	Thick	Ld/Wid.M lb/in	Ld/A Max lb/in2	Ld/Wid.Y lb/in	Ld/A Yld lb/in2
	0.08	406.5	5081.25	217.7	2721.25
	0.082	430.3	5247.561	224.5	2737.805
	0.082	469.7	5728.049	223.2	2721.951
	0.082	462.7	5642.683	216.5	2640.244
	0.081	284.3	3509.877	221.8	2738.272
	Mean	410.7	5041.884	220.74	2711.904
	Std. Dev.	67.18	802.83	3.12	36.58

2 x 30%	Thick	Ld/Wid.M lb/in	Ld/A Max lb/in2	Ld/Wid.Y lb/in	Ld/A Yld lb/in2
	0.079	381.7	4831.65	217.5	2753.16
	0.08	401.1	5013.75	224.1	2801.25
	0.08	447.3	5591.25	224.7	2808.75

0.085	419.8	4938.82	242.5	2852.94
0.08	429.5	5368.75	225.4	2817.50
Mean	415.88	5148.84	226.84	2806.72
Std. Dev.	22.69	285.33	8.33	32.11

5 x 30%

Thick	Ld/Wid.M lb/in	Ld/A Max lb/in2	Ld/Wid.Y lb/in	Ld/A Yld lb/in2
0.083	397.8	4792.77	231.8	2792.77
0.078	322.7	4137.18	216.1	2770.51
0.087	396	4551.72	242.3	2785.06
0.08	395.4	4942.50	219.9	2748.75
0.081	415.6	5130.86	225.8	2787.65
Mean	385.5	4711.01	227.18	2776.95
Std. Dev.	32.28	343.86	9.25	15.92

15 x 30%

Thick	Ld/Wid.M lb/in	Ld/A Max lb/in2	Ld/Wid.Y lb/in	Ld/A Yld lb/in2
0.082	468	5707.32	239.6	2921.95
0.08	439.8	5497.50	218	2725.00
0.081	481.1	5939.51	239.2	2953.09
0.081	371.9	4591.36	225.4	2782.72
0.082	376.1	4586.59	223.6	2726.83
Mean	427.38	5264.45	229.16	2821.92
Std. Dev.	45.60	568.98	8.71	97.14

2 x 65%

Thick	Ld/Wid.M lb/in	Ld/A Max lb/in2	Ld/Wid.Y lb/in	Ld/A Yld lb/in2
0.084	473.5	5636.90	233.9	2784.52
0.083	361.6	4356.63	232.1	2796.39
0.079	435.2	5508.86	217.5	2753.16
0.082	476.2	5807.32	225.8	2753.66
0.082	383.2	4673.17	220.4	2687.80
Mean	425.94	5196.58	225.94	2755.11
Std. Dev.	46.56	573.39	6.38	37.70

5 x 65%

Thick	Ld/Wid.M lb/in	Ld/A Max lb/in2	Ld/Wid.Y lb/in	Ld/A Yld lb/in2
0.087	264.9	3044.83	244.5	2810.34
0.083	433.5	5222.89	233.4	2812.05
0.08	426.6	5332.50	241.6	3020.00
0.08	427.9	5348.75	220.8	2760.00
0.083	329.2	3966.27	235.6	2838.55
Mean	376.42	4583.05	235.18	2848.19
Std. Dev.	67.96	927.78	8.22	89.59

15 x 65%

Thick	Ld/Wid.M lb/in	Ld/A Max lb/in2	Ld/Wid.Y lb/in	Ld/A Yld lb/in2
0.081	310.1	3828.40	225	2777.78
0.081	411.9	5085.19	225.8	2787.65

0.081	425.8	5256.79	227.7	2811.11
0.08	229	2862.50	226.5	2831.25
0.081	247.8	3059.26	245.4	3029.63
0.081	230.7	2848.15	222.2	2743.21
Mean	309.2167	3823.38	228.7667	2830.11
Std. Dev.	90.01	1104.99	8.15	98.97

2 x 100%	Ld/Wid.M	Ld/A Max	Ld/Wid.Y	Ld/A Yld
Thick	lb/in	lb/in2	lb/in	lb/in2
0.082	435.7	5313.41	228.5	2786.59
0.081	433.9	5356.79	214.1	2643.21
0.082	434.8	5302.44	224.4	2736.59
0.089	451.7	5075.28	241.4	2712.36
0.08	423.8	5297.50	215.5	2693.75
Mean	435.98	5269.08	224.78	2714.50
Std. Dev.	8.96	99.13	9.90	47.33

5 x 100%	Ld/Wid.M	Ld/A Max	Ld/Wid.Y	Ld/A Yld
Thick	lb/in	lb/in2	lb/in	lb/in2
0.078	159.3	2042.31	159.2	2041.03
0.08	160.4	2005.00	160.3	2003.75
0.077	138.5	1798.70	138.5	1798.70
0.078	156.1	2001.28	156.1	2001.28
0.084	167.4	1992.86	165.2	1966.67
Mean	156.34	1968.03	155.86	1962.29
Std. Dev.	9.65	86.35	9.16	85.11

Appendix E

ERROR ESTIMATE DATA

HDPE TESTING IN ACID SOLUTIONS
DIMENSION MEASUREMENTS FOR ERROR CALCULATIONS
HDPE Testing; Quattro; hdpe-4

Sample	Length (in)	Width (in)	Thickness (in)
1	5.872	2.047	0.084
	5.893	2.037	0.080
	5.886	2.015	0.079
		2.023	
Avg.	5.884	2.031	0.081
Std. Dev.	0.01069	0.01427	0.00265
2	6.000	2.028	0.081
	5.995	2.030	0.082
	5.998	2.027	0.083
		2.025	
Avg.	5.998	2.028	0.082
Std. Dev.	0.00252	0.00208	0.00100
3	5.797	2.161	0.087
	5.821	2.152	0.092
	5.839	2.134	0.088
		2.128	
Avg.	5.819	2.144	0.089
Std. Dev.	0.02107	0.01537	0.00265
4	5.907	1.966	0.086
	5.938	2.080	0.085
	5.961	2.158	0.082
		2.212	
Avg.	5.935	2.104	0.084
Std. Dev.	0.02710	0.10677	0.00208
5	5.182	2.234	0.074
	5.128	2.304	0.081
	5.075	2.354	0.083
		2.411	
Avg.	5.128	2.326	0.079
Std. Dev.	0.05350	0.07518	0.00473

Sample	Length (in)	Width (in)	Thickness (in)
6	5.643	1.941	0.085
	5.625	1.935	0.080
	5.616	1.922	0.083
		1.913	
Avg.	5.628	1.928	0.083
Std. Dev.	0.01375	0.01263	0.00252
7	5.512	2.153	0.082
	5.493	2.164	0.082
	5.469	2.168	0.084
		2.170	0.083
Avg.	5.491	2.164	0.083
Std. Dev.	0.02155	0.00759	0.00096
8	5.865	2.010	0.084
	5.889	2.018	0.081
	5.892	2.015	0.081
		2.018	0.082
Avg.	5.882	2.015	0.082
Std. Dev.	0.01480	0.00377	0.00141
9	5.465	2.039	0.083
	5.480	2.035	0.085
	5.492	2.041	0.082
		2.046	0.085
Avg.	5.479	2.040	0.084
Std. Dev.	0.01353	0.00457	0.00150
10	5.527	1.938	0.081
	5.456	1.945	0.082
	5.454	1.954	0.078
		1.954	0.083
Avg.	5.479	1.948	0.081
Std. Dev.	0.04158	0.00776	0.00216

HDPE Testing Error Calculations

A. Weight Change

$\Delta W = f(W_1, W_2, \text{offset})$

$\epsilon_T = \sqrt{\sum \left(\frac{\epsilon_i}{x_i}\right)^2}$ $\epsilon_{w1} = \epsilon_{w2} \approx \epsilon_{offset} = 0.05g$

$x_{w1} \approx x_{w2} \approx avg \approx 14.498$

$\Delta W = \frac{w_1 - w_2}{w_1}$

$\epsilon_T = \sqrt{\left(\frac{\epsilon_{w1}}{W_1}\right)^2 + \left(\frac{\epsilon_{w2}}{W_2}\right)^2 + \left(\frac{\epsilon_{offset}}{W}\right)^2}$

$= \sqrt{\left(\frac{.05g}{14.498g}\right)^2 3}$

$= 0.00597 = 0.597\% \left(\frac{g\ error}{g\ total}\right)$

B. Volume Change

$\Delta V = f(L_1, L_2, W_1, W_2, T_1, T_2, \Delta Temp)$ $L_1 \approx L_2 \approx L_{Avg} \approx 5.595$

$W_1 \approx W_2 \approx W_{avg} \approx 2.017$

$T_1 \approx T_2 \approx T_{avg} \approx 0.0839$

$\epsilon_T = \sqrt{\left(\frac{.022}{5.595}\right)^2 \times 2 + \left(\frac{.025}{2.017}\right)^2 \times 2 + \left(\frac{.00217}{.0839}\right)^2 \times 2 + (0.0014)^2 \times 3}$

$= 0.0410$
$= 4.10\%$

C. Specific Gravity Change

$\Delta S.g. = f(W_1, W_2, L_1, L_2, W_1, W_2, T_1, T_2, \Delta Temp, \text{offset})$

$= \sqrt{(0.00168196)_{\text{from B}} + (0.00014280)_{\text{from A}}}$

$= 0\ 0.0427$
$= 4.27\%$

HDPE Testing — Dimension Error Calculation

Basis: a) Straightedges marked on guillotine
Therefore, for L and W, I am measuring error on guillotine cutting plus error of micrometer measuring technique
b) Thickness error is due to manufacturing process quality in producing sheet of uniform thickness and how frequently the thickness varies

Measured three samples in several places:

Sample	L	W	T
1	5.872	2.047	0.084
	5.893	2.037	0.080
	5.886	2.015	0.079
		2.023	
Avg =	5.884	2.030	0.081
$S.D._{n-1}$ =	0.01069	0.01427	0.002646
2	6.000	2.028	0.081
	5.995	2.030	0.082
	5.998	2.027	0.083
		2.025	
Avg =	5.998	2.028	0.082
$S.D._{n-1}$ =	0.002517	0.002082	0.001000
3	5.797	2.161	0.087
	5.821	2.152	0.092
	5.839	2.134	0.088
		2.128	
Avg =	5.819	2.144	0.089
$S.D._{n-1}$	0.02107	0.01537	0.002646

See continuation Sheet for more data
Data doesn't seem close enough for statistical validity

$S.D._{avg} = 0.0220$
$S.D._{avg} = 0.0250$
$S.D._{avg} = 0.00217$

$$\epsilon_T = \sqrt{\sum\left(\frac{\epsilon_i}{x_i}\right)^2}$$ for + − × ÷ (all linear operations)

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